SPATIAL AND TEMPORAL ANALYSIS OF EXTREME MIDWESTERN BLIZZARD STORM TRACKS AND SUBSEQUENT FEDERAL DISASTER DECLARATIONS

BY

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In honor and memory of my biggest academic fan . . .
My father, Frederick Atkinson

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Abstract

Using the NOAA Central Library United States Daily Weather Maps Project, the Hydrometeorological Prediction Center (HPC) online weather charts, *Storm Data* records from the National Climatic Data Center (NCDC), and the Academic OneFile from the University of Kansas, this study identified 145 extreme Midwestern blizzards, defined as storms with minimum central pressures at or below 992 mb, occurring between September 1, 1966, and May 31, 2008. This 42-year time period was split into two 21-year segments for comparative analyses of any changes in the spatial and temporal character of these storms: 1) September 1, 1966-May 31, 1987 (Time Period I: 79 blizzards); and, 2) September 1, 1987-May 31, 2008 (Time Period II: 66 blizzards). Changes in the frequency and intensity of extreme Midwestern blizzards proved to be statistically insignificant.

All 145 blizzards in Time Periods I and II were mapped using ArcGIS 9.3 with data from the GISS Atlas of Extratropical Storm Tracks and the HPC weather maps and charts online resource. A 50-km buffer flanked each storm track and helped account for any uncharted errors in the original re-analysis procedures done by the GIS. Additionally, the 50-km buffer provided a construct for identifying the trajectory for each snowstorm within the 12-state study region, defined as North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, Michigan, Illinois, Indiana, and Ohio. This study indicated a statistically insignificant southward shift of the median storm track in Time Period II.

Of the 79 blizzards in Time Period I and the 66 blizzards in Time Period II, only 23 storms (6 in Time Period I and 17 in Time Period II) resulted in federal emergency and disaster declarations (FEDD). Logistic regression analyses of seven independent variables utilizing the Forward LR model failed to accurately predict when FEDDs occurred. In contrast, the total

number of counties declared as FEDDs increased from 378 (Time Period I) to 973 (Time Period II), a statistically significant difference. The spatial distribution of declaration hazards (snow and ice) contributing to FEDDs changed between the two time periods, indicating a pattern not necessarily connected to the expected climatology of extreme Midwestern blizzards.

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Chapter 1: Introduction

1.1 Background

Early Midwestern pioneers, settlers to virgin prairie and growing cities, faced a constant wintertime threat: blizzards. Many settlers to the American Heartland, the Midwest, came from northwestern Europe and needed to adapt to a harsher cold-season climate. Coming from countries such as Ireland, the United Kingdom, and Norway, these New World pioneers knew milder winters. Those mild winter days ended on the American Plains. Farm families learned quickly the new ways of the "Snow Winter"(Laskin 2005), sometimes enduring several blizzards in one season, as epitomized in Wilder's (1953) popular fictional account, *The Long Winter*. Sometimes rural populations needed to endure frigid temperatures along with blizzard snow. Laskin (2005) reported in *The Children's Blizzard* the temperature at North Platte, Nebraska, at 2 pm, central time, on January 12, 1888, was -19° C (-2° F), a 17 Celsius-degree (30 Fahrenheit degree) drop since 6 am, with winds recorded at 17.9 ms^{-1} (40 mi hr^{-1}). This temperature and wind combination created a wind chill of about -33.9° C (-29° F) (Lutgens and Tarbuck 2007). With respect to the dangers faced by Plains children and adults, rural residents were not the only ones facing hardships during early-American blizzards. Urban pioneers faced the challenges of heavy snow and wind too. Ludlum (1968) related that St. Louis, Missouri, picked up 35.6 cm (14 in) of snow in about eight hours on January 31, 1831.

Just like in the nineteenth century, blizzards continued to plague large cities in the twentieth century. On January 26-27, 1967, Chicago, Illinois, experienced one of the biggest blizzards to affect that area during the twentieth century. Snow started falling on the morning of January 26th and continued throughout the day, setting a new 24-hour snowfall record of 50.3 cm (19.8 in) and a new record storm total of 58.4 cm (23.0 in) when the storm attained a minimum central pressure reading of 989.7 mb as it entered Lake Erie (Smith 1967; Ward 1967). These severe winter weather conditions caused many hardships for local residents. Vonda Atkinson, then a high school English teacher in Hoffman Estates, Illinois, told of traveling 38.6 km (24 mi) back to Evanston, Illinois, during the late-afternoon hours of January 26th during the height of the storm. She recalled how everything was white on her return trip with the snow [in drifts] topping some cars at her place of residence in Evanston (Personal Communication, February 14, 2010). Smith (1967) reports snowfall totals of 30.5 cm (12 in) by the late-afternoon hours of January 26, 1967, a situation of hardship and hazard for the residents of Chicago and surrounding environs as they made their way home from work.

While the historical record of Midwestern blizzards is insightful, it reminds us that some of the complex challenges associated with Midwest winter-storm prediction remain as we move into the twenty-first century. Only now, the problem is complicated further: how to regionally predict where and to what degree extreme blizzards will continue to affect the Midwest within the context of climate change.

1.2 Statement of the Problem

Midwestern blizzards occur annually in the Midwest. The challenge in understanding these storms and how they may be changing within the context of climate change goes beyond global changes in temperature gradient and pressure patterns. The Chicago, Illinois, snowstorm of January 26-27, 1967, highlights the need for a better understanding of winter storms that affect cities, small towns, and farmsteads in the Midwest. North American storm tracks respond to large-scale (global) changes in temperature and pressure patterns, but it is difficult to know exactly how these global changes affect regional storm tracks, since Midwestern blizzards return annually and not on multi-year cycles. For example, Midwestern storm tracks probably will change with a modification in the Arctic Oscillation (AO) circulation system; however, it is difficult to know to what degree Midwestern storm tracks will shift from season to season because the AO forecasts a longer-term trend of probabilities and is not intended to specifically indicate storm track position or the number of Midwestern blizzards occurring at a certain time and place. Changes in North American storm track patterns resulting from pressure oscillations such as the AO needs to be augmented by more in-depth studies of annual winter weather patterns across the Midwest. Blizzards, being one of the most detrimental forms of winter weather experienced in the Midwest, demand a more thorough investigation and description of changes in storm tracks over time. Only by determining any changes in blizzard storm tracks will geographers and other scientists sufficiently augment their knowledge to ascertain which Midwestern areas may become more prone to damages resulting from future blizzards.

1.3 Purpose of the Study

This research has three main goals:

1) To ascertain the temporal and spatial characteristics of extreme Midwestern blizzard storm tracks.

2) To statistically relate the characteristics of extreme Midwestern blizzards to FEDD.

3) To ascertain the spatial relationship between FEDD and the extreme Midwestern blizzards responsible for creating these hazard scenarios.

1.4 Research Questions

In context of the research goals, this dissertation addresses the following questions as related to concerns about climate change affecting anomalous winter storms:

1) What is the spatial and temporal signature of extreme Midwestern blizzards and to what degree, if any, have these storms changed over time?

2) What is the relationship between FEDD, extreme Midwestern blizzards, and resulting damages?

1.5 Research Hypotheses

Stemming from the research questions, these research hypotheses drive the study:

1) As suggested by the Intergovernmental Panel on Climate Change (IPCC), it is expected that extreme Midwestern blizzards will decrease in frequency, increase in intensity, and shift northward over the 42-year study period.

2) Snowstorm-related, meteorological characteristics will accurately predict which blizzards typically result in FEDD.

3) Regardless of precipitation amount and to indicate how closely emergencies and disasters follow winter snowstorm climatology, it is hypothesized that presidential declarations due to snow will be located to the north and west of blizzard storm tracks, while ice-related hazards will be located to the south and east of storm tracks. Increases in federal declarations due to snow and ice are expected.

1.6 Significance of the Study

This research provides a starting point for assessing the spatial and temporal relationships between extreme blizzards and climate change in the Midwest. From this, the effects of climate change in relation to these snowstorms will become more apparent and could provide the foundation for further studies into how blizzards affect specific regions within the Midwest.

Another potential outcome of this study would be a more complete understanding of which extreme blizzard characteristics best determine the chance for presidential declarations. This type of information could be used as a first step toward better allocation of monetary and human resources in times of need.

Chapter 2: Literature Review

2.1 Past Studies of Blizzards

The Northern Plains and Midwestern regions of the United States dealt with perennial blizzard conditions during the early development and settling of this country. Before the term blizzard was coined in 1870, Detroit on January 5, 1784, experienced 'high wind and snow', as recorded by Dr. George C. Anthon (Ludlum 1966a, 222). Blizzards forced many settlers in the Midwest to endure storms of raging wind with swirling snow and ice, sometimes for two or three days while the elements blew unabated outside. The dawn of the 1800s brought many more blizzards to Midwestern settlers. One of the largest blizzards of the nineteenth century struck the Kansas City, Missouri, area on December 29, 1830, with 76.2 cm (30 in) of snow accompanied by 3-3.7 m (10-12 ft) drifts (Ludlum 1968). January 20, 1855, ushered in more severe winter weather for Lee County, Iowa, with heavy winds and a deposit of 61.0 cm (24 in) of snow at Fort Madison in the southeast part of the state (Ludlum 1968). One of the most severe blizzards impacted a large portion of the Midwest during the winter of 1856-1857. From December 1-3, 1856, in Platteville, Wisconsin, a snow-filled blizzard marooned the town and left it reeling in the wake of 35.6 cm (14 in) of snow (Ludlum 1968). The same storm also brought brutal northwest gales to Fort Kearney, Nebraska, on the 2nd of December (Ludlum 1968). About ten years later on January 24-25, 1867, city residents in Milwaukee, Wisconsin, experienced winter hardships of their own after a blizzard piled nearly 61.0 cm (24 in) of snow on the community (Ludlum 1968). Before the official establishment of North and South Dakota, Ludlum (1968) tells of the Dakota blizzard of 1868 at Fort Stevenson, a hardship for both mind and body as the wind blew for several days. The hardships of extreme Midwestern blizzards were not solely reserved for European men and women as proven during the snowstorm of March 14-16, 1870, the storm in which the term blizzard was coined by an Estherville, Iowa, newspaper (Ludlum 1968): the White Earth Reservation in Minnesota received 40.6 cm (16 in) of snow during the snowstorm (Ludlum 1968). Even though this type of storm was now named, blizzards continued to plague the Great Plains and Midwest in the 1880s.

While not trying to lessen the hardships faced by East Coast residents dealing with severe blizzards of their own (Kocin 1988; Kocin 1983), rural families of the Midwest in the 1880s experienced some psychological and physical effects due to extreme blizzards. One survivor remembered some unpleasant realities associated with the howling and screaming winds of the January 28, 1887, blizzard: frozen children, crazy women, suicidal men, and ice-clad cattle (Morris 1986). On January 12, 1888, two months before New York City and portions of the East Coast suffered from the famous blizzard of March, 1888 (Kocin 1983; Hughes 1981), an Alberta Clipper-type blizzard pushed south from Canada with frigid temperatures, snow, and high winds. The storm, coined the “Children’s Blizzard” advanced quickly through the Dakotas before arriving in Nebraska just as the schoolchildren were being released from country schools and started making their way home (Laskin 2005). Severe blizzard winds blew out of the north with peak gusts at Bismarck, North Dakota, Huron, South Dakota, and Topeka, Kansas, recorded at 24.1 ms^{-1} (54 $mihr^{-1}$), 26.8 ms^{-1} (60 $mihr^{-1}$), and 29.5 ms^{-1} (66 $mihr^{-1}$) respectively (Ludlum 1970d). During the “Children’s Blizzard”, hypothermia invaded many of the young children’s bodies after they became disoriented and were forced to seek shelter huddled in hay bales or whatever other scant coverings could be found (Laskin 2005). Even though the rural and urban residents have become more accustomed to winter living in the Midwest, blizzards continued to affect their livelihoods on the farms, in the cities, and on the Great Lakes in the twentieth century.

One of the most extreme blizzards struck the Midwest on November, 11, 1940, the infamous Armistice Day Blizzard. While the storm affected a wide range of residents in the region from excited duck hunters to ill-clad retail workers, fruit and livestock farms sustained the most severe losses. A wide variety of fruit trees suffered damage since many of the trees had not yet hardened for the winter. Apple trees were especially hard hit in Iowa. Rich Pirog, education coordinator for the Leopold Center for Sustainable Agriculture at Iowa State University, indicated that the loss of trees either from freezing or severe damage resulted in an 85 percent reduction in the 1941 apple crop (Pirog 2009). In addition to orchards and local fruit farms, Iowa livestock suffered tremendous losses too: an estimated 153,700 cattle, sheep, hogs, and turkeys perished during the blizzard (Knarr 1941). During the overnight hours of November 10th and the early morning hours of November 11th, the storm drew ever closer to some of the larger Midwestern cities.

Many city workers were not ready for the Armistice Day Blizzard. Temperatures early in the morning started off very mild for the second week in November. The temperature in Chicago, Illinois, fell 24° C (43° F) during the course of the day (Knarr 1941). This rapid cooling found many people dressed scantily, considering the unexpected change in weather during the course of the workday. Some workers in Minneapolis, Minnesota, struggled to get home in the blizzard because the streetcars had stopped operating during the height of the storm, forcing many to trudge through mounds of snow with no boots or heavy coats (Keller and O'Meara 2006; Hull 2004; Douglas 1990). Snow accumulated quickly with many locations in Iowa and Minnesota receiving at least 30.5 cm (12 in) of snow by the conclusion of the storm (Keller and O'Meara 2006; Hull 2004; Douglas 1990; Knarr 1941). Storm fatalities varied with Hull (2004) reporting a range between 39 and 59 in Minnesota and a nationwide tally of 144 lost, while Knarr (1941) cited the count as 87 within Iowa, Illinois, Indiana, Michigan, Minnesota (49 died in Minnesota in Knarr's report), and Wisconsin.

Just as on land, when severe Midwestern blizzards move over the Great Lakes, these storms adversely affected crews aboard lake freighters. Two extreme storms affected a large number of men and boats in the first half of the twentieth century. In November, 1913, a severe Great Lakes storm, called the "White Hurricane" crossed Lake Huron and claimed approximately 250 men (Brown 2002). Many sailors crossing the Great Lakes during the Armistice Day Blizzard met a similar fate to those who perished in the 1913 storm. Knarr (1941) reported that sailors on Lake Michigan faced the brunt of southwesterly storm winds with three boats lost at the price of 59 men. Unfortunately, the dangers faced by Great Lakes sailors as a result of blizzards continued into the second half of the twentieth century.

The dawn of November 9, 1975, reflected the mild temperatures that are hoped for by all during the autumn months in the northern regions of the Midwest. During this balmy day, the *Edmund Fitzgerald* left the Duluth-Superior harbor and entered the open waters of Lake Superior. The following evening, Monday, November 10, 1975, at about 7:15 pm, the 729-foot lake freighter was lost off radar in a blinding snowstorm taking all 29 men down in one of the most historic and mysterious shipwrecks in the annals of the Great Lakes. No one knows exactly why she sank, but the weather, a snow-filled storm over Lake Superior, might have played a role in the ship's demise (Keller and O'Meara 2006; Bentley and Horstmeyer 1998; Hemming 1981). Like the *Edmund Fitzgerald* storm of November 10, 1975, three other blizzards of note deepened rapidly and provide good examples of blizzard characteristics and the resulting hardships for some residents of the Northern Plains and Midwest.

The first of these blizzards occurred on March 2-5, 1966, in North Dakota, South Dakota, and Minnesota. After a period of warmer weather, winter turned dark, windy, and snowy once again. The lee-side low pressure center tracked southeast from the northern Rocky Mountains toward Colorado. It then deepened to 984 mb while following a northeasterly route toward Nebraska, South Dakota, and Minnesota. At maturity, the storm blew incessantly over North Dakota with some winds in excess of 35.8 ms^{-1} (80 $mihr^{-1}$) with gusts to 44.7 ms^{-1} (100 $mihr^{-1}$) while snowfall piled up to 50.8-76.2 cm (20-30 in) in a continuous swath extending from northern South Dakota across to north-central Minnesota with drifts approaching 12.2 m (40 ft) in some locations (Ramsey and Skroch 2004).

The second of these dangerous snowstorms arrived on January 10, 1975, and lasted three days. Many areas in central and north-central Minnesota received over 50.8 cm (20 in) of snow with very strong winds. Eighty deaths occurred in the storm, which set a record low atmospheric pressure reading of 966.8 mb at Duluth, Minnesota (Graff and Strub 1975). In addition, this same storm produced blizzard conditions in the southern Prairie Provinces of Canada (Babin 1975).

Lastly, the Halloween Blizzard of October 31-November 2, 1991, caught Iowa, Minnesota, and Wisconsin off-guard. With just over 71.1 cm (28 in) in the Twin Cities and nearly 94.0 cm (37 in) in Duluth, Minnesota, the storm was unprecedented even according to Minnesota standards. It was one of the earliest snows, setting numerous records, including most snow in October (20.8 cm/8.2 in) and most snowfall for the Twin Cities during one blizzard event (72.1 cm/28.4 in) (Keller and O'Meara 2006). Iowa suffered many losses due to ice: crop and utility losses were estimated at $5 million and $63 million 1991 dollars respectively (Keller and O'Meara 2006), indicating the extensive damage to local infrastructure.

These snowstorms highlight the potential for dangerous winter conditions and related damages due to snow, ice, and wind in the Midwest. All together, the three blizzards inflicted much hardship and resulted in at least 118 deaths (Keller and O'Meara 2006; Ramsey and Skroch 2004; Graff and Strub 1975).

2.2 Characteristics of Midwestern Blizzards

The term blizzard was first coined during a snowstorm in March of 1870 by the Esterville, Iowa, newspaper, the Vindicator (Ludlum 1968). The NWS defines a blizzard as a severe winter storm with the following criteria: A blizzard is a significant winter weather event with sustained winds of 15.6 ms^{-1} (35 $mihr^{-1}$) reducing visibility to 0.40 km (0.25 mi) or less for a minimum of three hours due to falling and/or blowing snow (NWS 2010f).

The Northern Plains and Midwest experience the greatest frequency of blizzards in the conterminous United States. In a study of 438 blizzards in the contiguous United States occurring between 1959 and 2000, Schwartz and Schmidlin (2002) showed that the Northern Plains and parts of the Upper Midwest annually experience the greatest number of blizzards. Specifically, the counties of northwestern Minnesota and eastern North Dakota, average 2.4 blizzards per year (Schwartz and Schmidlin 2002). Understanding the distribution and frequency of blizzards within the Midwest and Northern Plains sometimes can be difficult to ascertain since this information is often couched within the context of other winter storm studies. Changnon, et al. (2006) analyzed snowstorms with snowfall exceeding 15.2 cm (6 in) occurring between 1901 and 2001, indicated similar results to Schwartz and Schmidlin (2002), of about 2 blizzards per year near the Canadian border. In addition, other studies have indicated the rare occurrence of blizzards in the Midwest (Branick 1997; Houston and Changnon 2009). Blizzard frequency can vary depending on the topography and vegetation characteristics of a local region. Dery and Yau

(1999) found in a study of the Mackenzie River Basin in the Canadian arctic that blizzard frequency was ten times less likely in the taiga versus the tundra because evergreen trees proved effective in reducing wind velocities. Inter-annual variability of blizzards is significant with some winter seasons producing more storms than others. During the winter of 1996-1997, Grand Forks, North Dakota, recorded nine blizzards (Osborne 1997; Todhunter 2001), compared to an annual average of less than two storms per year. In addition, blizzards occur with regularity downwind of the Great Lakes, producing ample amounts of snowfall during the ice-free portions of the winter season (Falconer, et al. 1964; Dewey 1977). While blizzard frequency and proximity to the Great Lakes helps influence regional storm impacts, snowstorm size and forward speed need to be considered too.

Areal extent and forward speed of snowstorms and blizzards vary across the Midwest and Northern Plains. In studies of snowstorms and blizzards east of the Rocky Mountains, storm size parameters change according to the time period and study methodologies utilized by different researchers. Changnon, et al. (2008a) estimated the mean size of 241 large snowstorms east of the Rocky Mountains producing heavy snow (> 15.2 cm; 6 in) from 1950-2000 at 258,000 km^2 (~ 99,614 mi^2). Contrastingly, Changnon and Changnon (2007) studied 2,305 snowstorms occurring between 1950 and 2000 in the central and eastern United States and determined a mean size of 107,380 km^2 (~ 41,460 mi^2). Schwartz and Schmidlin (2002) calculated the mean area affected per blizzard from 1959-2000 as 150,492 km^2 (~ 58,105 mi^2). In addition to blizzard size, Changnon, et al. (2008a) estimated that extratropical cyclones posted average speeds between 805 and 1287 km day^{-1} (20.8-33.2 $mihr^{-1}$). As these blizzards move across the Midwest and Northern Plains, the full impact of these snowstorms also depends on their region of cyclogenesis and storm track trajectory.

Two main regions of snowstorm (blizzard) formation are recognized for areas in the Midwest and Northern Plains. Colorado lows (generally moisture-rich low pressure systems forming in eastern Colorado) and Alberta Clippers (generally fast-moving, moisture-starved low pressure systems forming in the prairies of Alberta) advance either in a northeasterly or southeasterly direction into the Midwest and Northern Plains (Black 1971; Reitan 1974; Zishka and Smith 1980; Osborne 1997; Todhunter 2001; Changnon and Changnon 2007; Changnon, et al. 2008a). While most blizzards track southeast from Alberta or northeast from Colorado, there are some exceptions. Some Midwest snowstorms do not originate in Colorado or Alberta. In a study of Indiana heavy-snow (≥ 10.2 cm or 4 in) events from 1966-1996, Bierly (2001) found only 41.7 percent (15/36) originating in Colorado. The 1991 Halloween Blizzard, while only one storm, hints at the wide variation in Midwestern storm tracks and supports the findings suggested by Bierly (2001). The Halloween Blizzard affected portions of Iowa and Minnesota from October 31-November 2, 1991, tracking in a near-northerly direction from around Houston, Texas, to Lake Superior before crossing into Ontario (GISS Atlas of Extratropical Storm Tracks (1961-1998) 2007). Regardless of regional origin, the rate at which Midwestern blizzards deepen varies markedly.

Snowstorms (blizzards) tracking toward the Midwest from initial cyclogenesis regions in the Rocky Mountains, Alberta, and the Southern Plains intensify at differing rates. Most blizzards that track in a northeasterly direction toward the Midwest deepen at a rate of 0.8 mb hr^{-1} (Salmon and Smith 1980). If a developing wintertime low pressure system follows a northeasterly storm track, the blizzard normally enters the Great Lakes region. As these snowstorms/blizzards enter the Great Lakes region, deepening generally occurs more readily during the ice-free “unstable season”, defined as the time of year when the water temperature of the Great Lakes is warmer than the ambient air temperature (Eichenlaub 1979; Angel and Isard 1997). Some low pressure systems associated with blizzards attain minimum central pressures well below 1013.25 mb (29.92 in Hg), defined as average barometric pressure. While not exclusively a study of blizzards, Changnon, et al. (2008a) found 67 percent of snowstorms in their study had minimum central pressures between 980 and 999 mb. An Ohio blizzard in the late 1970s provides an example of a snowstorm's rapid deepening into a blizzard. The January 26, 1978, Ohio blizzard strengthened rapidly to bomb cyclone status, defined as a 12 mb decline in central pressure in 12 hours (Sanders and Gyakum 1980). The maximum rate of intensification for this storm was 40 mb in 24 hours or 3.3 mb hr^{-1} with a minimum central pressure reaching 955.5 mb (Salmon and Smith 1980). While anomalous, the 1978 Ohio blizzard indicates the potential for snowstorm deepening along the baroclinic zone (Saylor and Caporaso 1958). Moderate or rapid blizzard intensification can lead to regional or widespread impacts from snow, wind, and ice.

Precipitation from Midwestern blizzards falls as wind-whipped snow, ice, or snow and ice. The distance to the heaviest snow bands in Midwestern blizzards vary but generally lie to the north and west of the surface low pressure track (Goree and Younkin 1966; Changnon, et al. 2008a) or 850 mb low pressure track (Browne and Younkin 1970). Occasionally, blizzard snowfall rates exceed 5.1 cm hr^{-1} (2 in hr^{-1}) (Pettegrew, et al. 2009). At other times, sleet occurs in conjunction with Midwestern blizzards, and this type of mixed precipitation is most likely to occur in January in the Northern Plains (Changnon 2008b). The most severe Midwestern blizzards exhibit coldwaves when the combination of rapidly falling temperature and strong northerly winds create dangerous wind chills as the storm passes (Wendland 1987). The hypothetical combination of 91.4 cm (36.0 in) snowfalls during the 1991 Halloween Blizzard

(USHCN 2006), 40.6° C (73.0° F) temperature drops like the one at Columbia, Missouri, on November 11, 1911 (Wendland 1987), and wind gusts of 30.8 ms^{-1} (69 $mihr^{-1}$) as experienced at Dayton, Ohio, during the January, 1978 blizzard (Salmon and Smith 1980) highlight the importance of elucidating whether extreme weather events like Midwestern blizzards are changing spatially and temporally in the context of climate change.

2.3 Blizzard Formation in the Midwest

Extreme Midwestern blizzards form from regular snowstorms only when certain favorable meteorological conditions are present in the atmosphere. From a meteorological standpoint, the best opportunity for blizzards is when several important factors come together and lead to storm development. Three important factors will be mentioned here: 1) baroclinic instability; 2) the frontal structure; and, 3) the pressure gradient and resulting cyclonic airflow.

Baroclinic instability is a complex series of changes that occur along the baroclinic zone, defined as "layers" associated with a rapid temperature change along a 100-km frontal discontinuity (Neiburger, et al. 1973). The baroclinic zone is very important because the developing surface temperature gradient provides potential energy for the deepening extratropical cyclone. From the surface to jet stream level, a snowstorm grows ". . . whenever the density [temperature] varies in surfaces of constant pressure (Neiburger, et al. 1973).

Surface frontal discontinuities naturally develop from well-established baroclinic zones within extratropical cyclones. As a 1000 km (620 mi)-wide frontal cyclone grows in intensity, the surface temperature, pressure and wind patterns associated with the cold front (the surface discontinuity) become more evident and pronounced – and it is these differences that contribute to instability along the frontal (baroclinic) zone. This instability associated with the baroclinic zone allows for cloud formation within the blizzard and subsequent precipitation in the warm and cold sectors of the storm.

Behind the cold front, continental polar or arctic air supplies the very cold conditions necessary for snow production in the northwestern quadrant of the extratropical cyclone. In some snowstorms, it is thought that very cold air associated with a tropopause fold descends, chills the Earth's atmosphere, and supplies the cold air necessary to support sustained snowfall in the lower atmosphere below 850 mb (Djuric 1994). In conjunction with the deepening surface low pressure system, higher pressures sometimes dominate the surface environment far to northwest of the advancing cold front. A pressure gradient then exists between the two surface features, potentially supporting blizzard-producing winds (Moran and Morgan 1997).

Blizzard conditions can also occur in the region north of the warm front. Weisman, et al. (2002) explored snowfall associated with what he termed "inverted fronts." One of the characteristics of inverted fronts is the production of snowfall and other types of winter precipitation north of the traditional warm front. In six cold seasons (September thru April) from 1989-1995, 247 frontal cyclones were evaluated with 103 producing precipitation in the northeastern sector (Weisman, et al. 2002). If these frontal cyclones become well-developed, strong winds from the east or northeast could, in the presence of snow, reduce visibilities similar to blizzard conditions.

The development of blizzard conditions usually requires moist and dry air associated with the warm and cold conveyor belts contributing to snowstorm instability and rising air motion within the snowstorm. By colliding with the easterly and northeasterly winds associated with the maritime (moist) polar air mass north of the warm front, there may be, depending on the moisture levels and the temperatures of the air masses, the potential for sustained upward vertical motion within the sub-regions of the existing cloud, thereby enhancing the precipitation regime of the extratropical snowstorm (Barry and Chorley 1970).

The winds that blow falling snow into whiteout conditions occur when a firmly established pressure gradient exists within an extratropical cyclone. Within the low pressure system at the surface, pressure differentials contribute to both horizontal and vertical airflow. Surface air movement is directly correlated to isobaric differences near the ground, while vertical uplift is approximately 1 cm s^{-1} (Wallace and Hobbs 1977). As vertical air motion increases near the center of low pressure, surface storm winds also increase in intensity.

The amount of wind strengthening that occurs at the surface depends on the amount of upward vertical motion present within the storm. Significant upward motion in the storm column (the region above the surface low pressure core) occurs in conjunction with upper-level divergence, located midway between the upper-level trough and ridge. As such, the greatest amounts of upward vertical motion are realized in conjunction with ample divergence at the jet stream level (downstream from the upper-level trough) (Eagleman 1985).

The degree to which blizzard winds increase in velocity is directly related to snowstorm deepening. Assuming divergence aloft (at jet stream level), converging air below at the low pressure center easily moves upward, and this action potentially supports a rapidly strengthening storm and an increased surface pressure gradient, thus creating positive feedback regarding the magnitude of surface storm winds. Once a gradient has been established on the surface, air begins to move from high to low pressure in an attempt to equalize the differences (Barry and Chorley 1970). The rate of airflow is governed by the magnitude of the pressure gradient, indicating the velocity of blizzard winds is controlled by the actual rate of pressure change existing along the storm's isobaric surface. In the presence of dry snow (either ground-based or falling), a blizzard can ensue:

> . . . if a cold area of high pressure does not exist north of a developing area of low pressure, the storm will likely be less intense. As diverging winds at high elevations over the winter storm remove more air, the air pressure in the center of the storm continues to fall. As the difference in pressure between the center of the storm and the high-pressure area north of the storm increases, winds around the storm blow faster. These strong winds can cause significant blowing and drifting snow, reducing visibility to mere yards at times in blizzard conditions (Stein 2001).

In the presence of dry snow, air blowing counterclockwise around low pressure in the Northern Hemisphere, characterized by converging surface winds in the presence of rapid upward motion, creates blizzard conditions in some snowstorms.

2.4 Midwestern Blizzards in the Context of Climate Change

High-intensity blizzard events do not occur very often during the Midwestern cold season. An inverse relationship exists between snowstorm intensity (as measured by barometric pressure) and frequency. Very strong storms rarely occur, while "average-strength" extratropical cyclones form with much more regularity. The IPCC (2007) summarizes storm trends as follows:

> Trends in the number and intensity of extreme events in North America are variable, with many (e.g., hail events, tornadoes, severe windstorms, winter storms) holding steady or even decreasing (Kunkel, et al. 1999; McCabe, et al. 2001; Balling and Cerveny 2003; Changnon 2003; Trenberth, et al. 2007).

Future Midwestern blizzard events are expected to be less frequent and more intense in the years to come. The IPCC (2007) states that atmospheric warming of 0.7° C in the last century will lead to changes in weather.

Changes in weather extremes like blizzards create difficulties in prediction due to their rarity. Various scientists and experts outside the climatology field disagree as to the severity of climate change to be expected. Some scientists believe the lack of a historical record regarding winter storms makes it very difficult to convincingly state that extreme weather events like blizzards are trending upward (Easterling, et al. 2000).

Since the IPCC's Fourth Assessment Report (AR4) in 2007, some scientists disagree with the conclusion put forth by Easterling, et al. 2000. Füssel (2009) suggests that portions of AR4 are already outdated and further assessments since that time have indicated "many risks are now assessed as stronger than in AR4, including the risk of . . . substantial increases in . . . extreme weather events . . . (p. 469)." This prognostication by Füssel (2009) builds upon some of the past concerns highlighted in the 2001 IPCC assessment report. One of the main concerns revolved around the changes in extreme weather events and other consequences forecast by the rise in temperature at the end of the twentieth century. Since AR4, Wahl and Ammann (2007) stated ". . . the primary conclusion of Mann, et al. (1998) . . . [shows] . . . that both the 20th century upward trend and high late-20th century hemispheric surface temperatures are anomalous over at least the last 600 years (p.33-34)." Sillman and Roeckner (2008) agreed with Wahl and Ammann (2007) that late-twentieth century temperature spikes and predicted future extreme climate events are outside the realm of natural climate variability. Even before these new studies, the IPCC (2007) through the use of the Atmosphere Ocean Global Circulation Models (AOGCM) affirmed the future conclusions asserted by Wahl and Ammann (2007) and Sillman and Roeckner (2008). As related to changes in extreme wintertime storms, the IPCC (2007) conclusions mirror the findings of a former study by Lambert and Fyfe (2006) in stating that an increase in greenhouse gases and CO_2 will consequently lead to a decrease in frequency and an increase in intensity of winter storms. Future winter storm characteristics also will depend on modifications to the spatial and temporal characteristics of Northern Hemisphere extratropical cyclones.

Klein (1958) found in a study of Northern Hemisphere cyclones and anticyclones occurring between January 1, 1899, and December 31, 1938, that low pressure systems developed fifty percent more often than high pressure systems. Low pressure systems in the conterminous United States varied by month between 1949 and 1976, averaging 84 in January and 50 in October (Reitan 1979). Given a warming atmosphere, Agee (1991) found a positive correlation to an increasing number of Northern Hemisphere cyclones. Lambert (1995) using the Canadian Climate Centre general circulation model found a reduction in the number of Northern Hemisphere wintertime low pressure systems with a corresponding increase in pressure-system intensities. Further, Lambert (1996) showed a sharp increase in twentieth century Northern Hemisphere winter cyclone intensities (≤ 970 mb) after 1970 with a greater number of these cyclones showing a positive baroclinic feedback correlated to higher sea-surface temperatures. Some studies show contrasting outcomes which do not fit neatly into the concept of decreasing storm frequencies with greater intensities. Zhang and Wang (1997), by utilizing the Community Climate Model with observational forcing from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis found three reasons for a decrease in wintertime surface cyclone activity: 1) atmospheric warming between the surface and 500 mb height; 2) a reduction in the land/ocean temperature gradient; and, 3) a decrease in the latitudinal temperature gradient due to greenhouse warming. Stephenson and Held (1993) used a Global Circulation Model (GCM) to suggest that Atlantic storm tracks may weaken and Pacific tracks do not change with increased CO_2 concentrations in the future. However, early GCMs contained some faults that should be considered (Sinclair 1999): coarse GCMs potentially underestimated the intensity of winter cyclone activity in CO_2 climate scenarios, a failing of the models to accurately represent the baroclinic region within extratropical cyclones. The conclusion by Sinclair (1999) was upheld when Ulbrich, et al. (2008) projected an increase of 5-8 percent in baroclinicity in the eastern North Atlantic by circa 2100 for the A1B/A2 Special Report on Emission Scenarios (SRES); however, the results proved to be insignificant, meaning the increased strengthening was not outside the natural variability of present-day climate conditions. Not all future results highlighted the shortcomings of the GCM. Chang and Fu (2002) indicated a 30 percent strengthening of the Pacific and Atlantic storm tracks in the 1980s and 1990s. Increases in the strength of Pacific and Atlantic storm tracks may affect midlatitude cyclone frequencies and intensities. In the Northern Hemisphere, McCabe, et al. (2001) found a statistically significant decrease in the frequency of midlatitude cyclones occurring between 1959 and 1997; during the same period, storm intensities showed statistically significant increases.

It is widely recognized that at the end of the twentieth century there was a significant change in the global climate (IPCC 2007). However, understanding how such global patterns affect society at regional and local scales requires examining how extratropical cyclones and related storm tracks might change in regard to their spatial, temporal, and intensity characteristics, as suggested by Chang and Fu (2002) and McCabe, et al. (2001). Additionally and to add complexity, changes in Northern Hemisphere extratropical cyclones and storm tracks are influenced by global pressure/temperature oscillations. To fully appreciate how extreme Midwestern blizzards may change in the future, these patterns need to be considered.

Where Midwestern blizzards occur in the future is linked to worldwide pressure patterns. Five of the oscillations linked to Midwest storm systems include: 1) the El Niño/Southern

Oscillation (ENSO); 2) the Pacific North American Pattern (PNA); 3) the Pacific Decadal Oscillation (PDO); 4) the North Atlantic Oscillation (NAO); and, 5) the Arctic Oscillation (AO). All of these oscillations vary in their temporal signatures. More importantly, any change in intensity or spatial patterns of these oscillations has the potential for modifying future blizzard patterns in the Midwest.

Even though the focus of this project is on Midwestern blizzards in the face of climate change, it is recognized that such changes are the result of changes in large-scale pressure patterns. Changes in global pressure patterns become even more important since a portion of the changes in extratropical low pressure systems will have to consider how these oscillations can affect storm tracks in the Midwest. A change in storm tracks threatens established patterns of Midwestern winter weather like blizzards. In addition, understanding changes in blizzard characteristics can be directly linked to weather impacts on society. By studying the ENSO, PNA, PDO, NAO, and AO, scientists hope to gain a better sense of how the potential for changing storm tracks may affect regional temperatures, precipitation patterns, and subsequent impacts in various regions of the United States like the Midwest.

The ENSO stands alone as the most familiar changing pressure circulation feature that affects global weather systems due to changes in the oceanic temperature pattern. Changing temperature patterns in the tropical Pacific, as linked to pressure changes over Australia and Tahti, contribute to warmer temperatures in the eastern Pacific near Peru and often lead to heavy rains, reduced fish (anchovy) catches, and changing weather patterns in the midlatitudes, through "teleconnections" (Glantz 1996). Teleconnections related to the El Niño phase of the ENSO vary across the Midwest; however, they generally result in milder conditions with warmer temperatures and less snow cover across the region (CPC 2010m; CPC 2010l). Conversely, the cold phase of ENSO, called La Niña, results in Midwestern conditions characterized by generally cooler than average temperatures across a large portion of the region (CPC 2010o). La Niña snowfall patterns across the Midwest varies more when compared to snowfall regimes during an El Niño period with northern regions receiving above-average amounts and southern regions below-average amounts (CPC 2010n).

While not the same as El Niño, the PNA affects regions in the Midwest too. The PNA is linked to the El Niño phenomena but on longer time scales with effects during the Midwest winter season remaining less defined. The PNA phases describe the position and intensity of the East Asian jet stream with the positive phase generally associated with El Niño and the negative phase with La Niña cycles (CPC 2010w). The link between the PNA phases and Midwestern wintertime temperature and snow patterns remain tenuous. From 1950-2000, the January temperature departure index (an index spanning the months December-February) as compared to the PNA phase show a positive correlation in North Dakota and South Dakota and a negative correlation in Ohio (CPC 2010v). In the January precipitation departure index (also spanning December-February) for the same time period (1950-2000), there was a negative correlation in precipitation with the PNA phase over Missouri, Wisconsin, Illinois, Indiana, Ohio, and Michigan (CPC 2010t). It remains very difficult to make any concrete statements regarding how the PNA will affect temperature and precipitation patterns in the Midwest because the correlations can be weak. In addition, the PNA indices only indicate certain phases and do not necessarily match certain winter weather conditions in the Midwest (CPC 2010u).

The PDO describes the changing temperature and pressure patterns associated with the North Pacific Ocean. The PDO is characterized by warm and cold phases. During the warm phase, the northeastern Pacific near North America and the west coast of the United States experiences warm sea-surface temperatures (SST) and low sea level pressures (SLP) across the interior North Pacific (Mantua 1999). Conversely, during the cold phase of the PDO, the northeastern Pacific SSTs cool as the SLP drops in the interior North Pacific (Mantua 1999). The PDO cycle lasts from 15 to 70 years, and during the twentieth century, it showed two warm periods and two cold periods (Mantua 1999). Caution needs to be exercised when looking for connections between the PDO and Midwestern winter weather, but generally above average snowfall comes to the Great Lakes in cold phase PDO scenarios (Mantua 1999).

The NAO describes the changing pressure patterns for the Icelandic Low (IL) and its implications for the eastern United States. The positive phase of the NAO usually indicates an increase in northern European precipitation and generally warmer temperatures for the eastern United States while the negative phase is characterized by less precipitation in northern Europe and colder temperatures in the eastern United States (CPC 2010p). Like the PNA and the PDO, the NAO varies across decades and influences the seasonal cold and snow patterns in the eastern United States. This Atlantic Ocean-based pressure oscillation has less influence on wintertime weather in the Midwest (CPC 2010s; CPC 2010q; CPC 2010r).

The AO describes pressure differences between the polar regions and the midlatitudes in the Northern Hemisphere. The negative phase of the AO generally exhibits low pressure at the midlatitudes (45° N) and higher pressures near the North Pole and is characterized by a greater probability of very cold continental polar or arctic air masses invading the Midwestern region of the United States (National Snow and Ice Data Center (NSIDC) 2010b). Like the El Niño/La Niña, PNA, and NAO oscillations, the AO has the potential to affect storm tracks in the Northern Hemisphere; however, the AO's proximity to the Midwest highlights its potential to significantly affect the climate patterns of this region. The AO varies in phase conditions both temporally and spatially, and these complications make it difficult to accurately predict the expected trends in Midwestern wintertime temperature associated with the AO. Historically, the AO positive (negative) phase exhibits above (below)-average Midwestern temperatures of 0.5-1.5° C (0.5-3.0° F) (CPC 2010c; CPC 2010e; CPC 2010g). The positive and negative phase AO snowfall patterns in the Midwest remain less clear-cut. The long-term trend indicates moderate variation in monthly snowfall with the only positive change coming during the December through February positive phase of the AO (CPC 2010b; CPC 2010d; CPC 2010f). According to the National Snow and Ice Data Center (NSIDC), the AO continues to sustain a mostly positive phase (NSIDC 2010b). If the AO were to switch phase (back to a mostly negative phase), the storm track regime and temperature profile for the Midwest may change, potentially leading to colder and snowier winter weather in the region.

Snowier Midwestern winter weather may also increase as atmospheric moisture content changes. Trenberth (1999) concluded that extreme storms are likely to become more severe because of the atmosphere's ability to hold water due to rises in air temperature. Rises in ambient temperature enhance the water-holding capacity of air, potentially contributing to a greater frequency of above-average rainfall and snow events. Groisman and Easterling (1994) showed that precipitation from both rain and snow increased in the Lower 48 by four percent during the last century, while precipitation over the Canadian prairies increased 19 percent between 1961 and 1995 (Akinremi, et al. 1999). Thus, the potential exists for precipitation extremes in future climate scenarios. Karl and Knight (1998) advocate further investigation into changes in precipitation in the United States. These investigations need to document the frequency and intensity of precipitation events because a warmer climate may foster a 50 percent reduction in return periods for some extreme precipitation events (Zhang, et al. 2001). Some studies suggest the increased regularity of extreme precipitation events is already a reality. Karl and Knight (1998) indicated the percentage of total annual precipitation coming from "heavy and extreme" precipitation events (> 90^{th} percentile) is increasing in the United States. Kunkel (2003) agreed indicating a "large increase" in the number of extreme precipitation events in the United States in the second half of the twentieth century. A greater percentage of the overall precipitation now comes from these anomalous events. Palecki, et al. (2005), in a study of 15-minute precipitation data from 1972-2002 in the eastern United States, showed increases in winter storm totals and duration. The delineation of extreme precipitation falling as rain or snow is more difficult to ascertain.

Watterson (2006) simulated winter rainfall increases of 14 percent between 2071 and 2100 under a global warming regime. As the United States progresses into the twenty-first century, wintertime precipitation may shift in location as temperatures warm. For example, regions considered snow-rich may find more rain mixed in with the snow. To highlight this, the expected Canadian snowfall (as opposed to other forms of precipitation) decreased in recent years, down 0.95 mm (0.04 in) per annum between 1961 and 1995 (Akinremi, et al. 1999). In a study of Canadian temperature change from 1895-1989, Skinner and Gullet (1993) calculated a rise in ambient temperature of about 1.1° C (1.3° F) per century, indicating the potential for freezing rain events in areas unaccustomed to freezing precipitation. Changnon and Karl (2003) showed that freezing rain varies annually in the Midwest (2-5 days) with no increasing or decreasing trend apparent. Like wintertime rainfall and freezing rain, snowfall is also tempered by ambient temperature. Karl, et al. (1993) cited a negative correlation between "area-averaged annual maximum temperature" and snow cover percentage in the contiguous United States. Snow cover (and antecedent snowfall) varies significantly over the Great Plains, where snow cover is negatively correlated to temperature (Robinson and Hughes 1991; Leathers and Robinson 1993). Contrastingly, Hughes and Robinson (1996) indicated that even with annual and interdecadal fluctuations, Great Plains snow cover shows an upward trend in recent decades. Some studies suggest that snowfall from extreme events has been declining over time. Berger, et al. (2002) in 50-year study of extreme (≥ 25.4 cm/10 in) snowstorms showed a decline of 43 percent in northwestern Missouri, suggesting large regional variability in snowstorm occurrence when compared to national trends. As a type of extreme snowstorm, Midwestern blizzards show large annual and inter-annual variability; thus, these storms epitomize the difficulties encountered when trying to describe their spatial and temporal characteristics within the context of climate change.

Stevens (1999) declares "heavy rainstorms and snowstorms" as probable within the context of global warming. Trying to define Stevens' (1999) statement proves a challenge. Balling and Cerveny (2003) skirt any true delineation of specific hazards but state that the occurrence of disasters, including blizzards, in the continental United States shows annual variability and, even though these types of storms are common during the cold season, it is not certain whether blizzard events show an increasing frequency over time. The researchers go on to indicate that "increases" may just be an artifact of population distribution and public perception. Even with this ambiguity regarding frequency, an aggregation of a number of studies give clues regarding intensity and potential snowfall within extreme Midwestern blizzards. Stewart (1991) stated that warm isothermal layers south and east of the low pressure track could lead to more unstable lapse rates as dry ground becomes exposed (and heated) in the presence of melting snow which may lead to sustained snowstorm growth and subsequent precipitation in future winter storms. Other scientists, like Namias (1985), insist that blizzards will be less intense because increased snow cover creates stability and retards future snowfall. The high albedo of newly-fallen snow tends to retard the rise in temperature that may have otherwise occurred over dry landscapes. If more snow is present on the landscape and melting is retarded, then the atmosphere has less capacity to hold moisture, potentially contributing to weaker extratropical cyclones due to lessened temperature and moisture gradients across surface fronts (Elguindi, et al. 2005). If the capacity for moisture in the atmosphere increases in the future, then the possibility for enhanced snowfall also becomes greater. Ross and Elliott (1996) utilized radiosonde observations between 1973 and 1993 and discovered a 3-7 percent increase in North American tropospheric water vapor from the surface to 500 mb. Kunkel (2003) and Trenberth, et al. (2003) both agree that more water vapor in the lower troposphere could lead to more intense snowfall events (like blizzards). In a moisture-rich environment, any infusion of continental polar air from Canada sets the stage for snowstorm deepening like occurred during the January, 1978, blizzard in Ohio where rapid intensification of the storm system progressed as southward moving arctic air refueled the baroclinic zone of the storm (Salmon and Smith 1980). Kunkel (2003) suggested that future extreme precipitation events like the January, 1978, Ohio blizzard are still difficult to predict due to their regional nature. Burton, et al. (1993) categorized blizzards as a type of regional hazard. If the aim is to better understand the spatial and temporal patterns of Midwestern blizzards as regional hazards, then mapping these snowstorms becomes a necessary step in comprehensively understanding these storms.

2.5 The Need for GIS and Statistical Analyses of Extreme Midwestern Blizzards

Blizzards as a form of extreme natural hazard have not been mapped extensively in geographical information systems (GIS) formats. If natural hazard events or effects are easily delineated or defined, then they attract more attention from a mapping standpoint. In terms of snow-mapping, past GIS projects focused on avalanche mapping (Mears 1980; Furdada, et al. 1995; Salzmann, et al. 2004). Midwestern blizzards seemingly attract little attention due, in part, to the largely low-risk nature of the central United States. Coppock (1995) highlighted this by a simple rubric: what is the size of the population at risk? To further clarify this point, East Coast blizzards like the "Superstorm" of March 12-15, 1993, (Kocin, et al. 1995) primarily attract attention because they intersect with the most densely population region of the United States. Sometimes the sheer magnitude of snow can produce a noteworthy impact even if the population at risk is not extremely large. For example, Kansas City, Missouri, during the winter of 2009-2010 experienced 112. 5 cm (44.3 in) of snow, which is 61.5 cm (24.2 in) above the 1971-2000 climatological average and ranks as the fourth highest winter-season snowfall in recorded history (NWS 2010d). Even though large seasonal snowfalls and blizzards are a perennial occurrence in the Midwest, there seems to be a gap in the GIS mapping of these storms. Hill and Cutter (2001) equate hazard risk to exposure, and blizzards may be viewed as a "generalized" risk. Satellite reconnaissance of extreme storms (Barrett and Hamilton 1982) and "nowcasting" (Wiesnet and Matson 1983) combined with theoretical discussions of the usefulness of GIS hazard mapping (Hodgson and Cutter 2001) or discussions regarding the usefulness and global potential of GIS for hazard mapping purposes (Peduzzi, et al. 2005) fail to delineate any regional or local hazard patterns for extreme blizzards when in fact those are the types of information needed for better locally-based decision-making. Rosenberg, et al. (1992) presents the need for agricultural resource modeling as a monitoring scheme for Nebraska, Kansas, Iowa, and Missouri farmers, as a proactive approach in response to climate change predictions. Practical applications as related to winter storms show another avenue to consider in better understanding severe Midwestern snowstorms. For example, Bocchieri (1979) utilized a logistic regression approach to predict probabilities for rain, freezing rain, or snow in a "best category" forecast. While not directly related to extreme Midwestern blizzard mapping, the Rosenberg, et al. (1992) and Bocchieri (1979) studies highlight the type of highly-detailed visual and statistical information necessary to delineate regional winter-weather patterns in the face of climate change. Future studies of Midwestern blizzards demand highly-detailed maps in combination with applied statistical analyses in delineating disaster-prone areas. Being able to effectively map, describe, and compare where Midwestern blizzards, as a type of natural hazard, have occurred in the past will provide a basis for assessing these snowstorms and related damages in the future.

Worldwide and in the United States the number of disasters due to natural hazards fluctuates. Chapman (1996) indicated that the number of natural disasters worldwide resulting in 25 or more deaths varies from year to year, but the overall trend is rising. As a type of natural hazard, blizzards in the United States create societal impacts in this country too. Schwartz (2005) reported that blizzards in the United States between 1959 and 2000 have accounted for 679 fatalities and 2,011 injuries. The average number of people affected by these blizzards was 2.46 million with a mean of $51.6 million (2001 dollars) in property damages per snowstorm.

Knowing and being able to map Midwestern blizzard areas prone to disaster becomes important in assessing damage and allotting federal monies in time of need. Between 1959 and 2000, a total of 25 blizzards resulted in disaster declarations (Schwartz 2005). Federal emergency and disaster declarations (FEDD) entitle counties most affected by extreme snowstorms to apply for aid.

State	Disaster Declarations	Emergency Declarations
Illinois	2	4
Indiana	2	3
Iowa	4	1
Kansas	8	1
Michigan	0	1
Minnesota	1	0
Missouri	6	2
Nebraska	5	0
North Dakota	4	1
Ohio	2	2
South Dakota	7	0
Wisconsin	0	2
Total	41	17

Table 2.1. Number of Disaster and Emergency Declarations: 1/1/00-3/31/10. Source: FEMA.

Table 2.1 indicates the Midwest has seen 58 PDDs since 2000 due to winter storms. Based on winter storms since circa 2000, Kansas, Missouri, and South Dakota experienced the greatest number declarations with 24 of 58 (41.4 percent).

The federal government sets the guidelines for how PDDs are awarded; however, other factors often drive which counties receive aid. Schmidtlein, et al. (2008) in a study of major hazard events, defined as the 95th percentile in terms of loss (those hazards accounting for losses greater than 1.58 million 2004 US dollars), across 18,278 counties between 1965 and 2004 found the number of PDDs to vary annually with an increasing trend over time and to be awarded based on past successes in receiving these monies. In addition to being able to recognize disaster-prone areas, the ability to map hazards effectively creates an opportunity to objectively assess whether monies are being awarded to counties based on the true spatial and temporal patterns of extreme Midwestern blizzards.

Chapter 3: Methodology

3.1 Study Area and Period of Study

Extreme blizzards for the time period from September 1, 1966, through May 31, 2008, were investigated in the Midwestern United States. For this study, the Midwest was defined as a twelve-state region including North Dakota, South Dakota, Nebraska, Kansas, Missouri, Iowa, Minnesota, Wisconsin, Michigan, Illinois, Indiana, and Ohio. This 12-state region was the base map for all subsequent maps in this study. The map shown in Figure 3.1 uses the Geographic Coordinate System (GCS) with the North American Datum (NAD) 1983. The GCS is not a projection; however, it was used because of its ease in mapping storm tracks based on latitude and longitude coordinates. An appropriate projection, such as the Alber's Equal Area, was difficult to use in properly aligning the storm tracks on the map; hence, the GCS was used. The overall time period consisted of two 21-year winter seasons. The first time period spans from September 1, 1966, through May 31, 1987, with the second ranging from September 1, 1987, through May 31, 2008. The start point, midpoint, and end point for the time periods were based on two main criteria: 1) the midpoint was chosen because the IPCC (2007), Chapter 4, on snow and ice mentioned there was a drastic reduction in seasonal Northern Hemisphere snowfall after the late 1980s. While not exactly centered in 1987, this breakpoint was within two years of the timeline cited in IPCC (2007); 2) the start point and end point were chosen, at least partially, based on the midpoint. It was desired to have two equal-length time periods. In addition, one of the main sources used for this research in determining what blizzards to include in the study largely was based on the *Storm Data* publication which started in 1959 and therefore set the absolute earliest start point. Further, I wanted to bring the research up to the present time, with the original idea for extensive research hatched in 2008. Given this, May 31, 2008, seemed like a good endpoint when dealing with severe snowstorms. Twenty-one years is the time frame from September 1, 1987 until May 31, 2008, so it was determined to compare two 21-year time periods for this study; hence, September 1, 1966, was decided on as the start point to ensure equal time sequences for comparison.

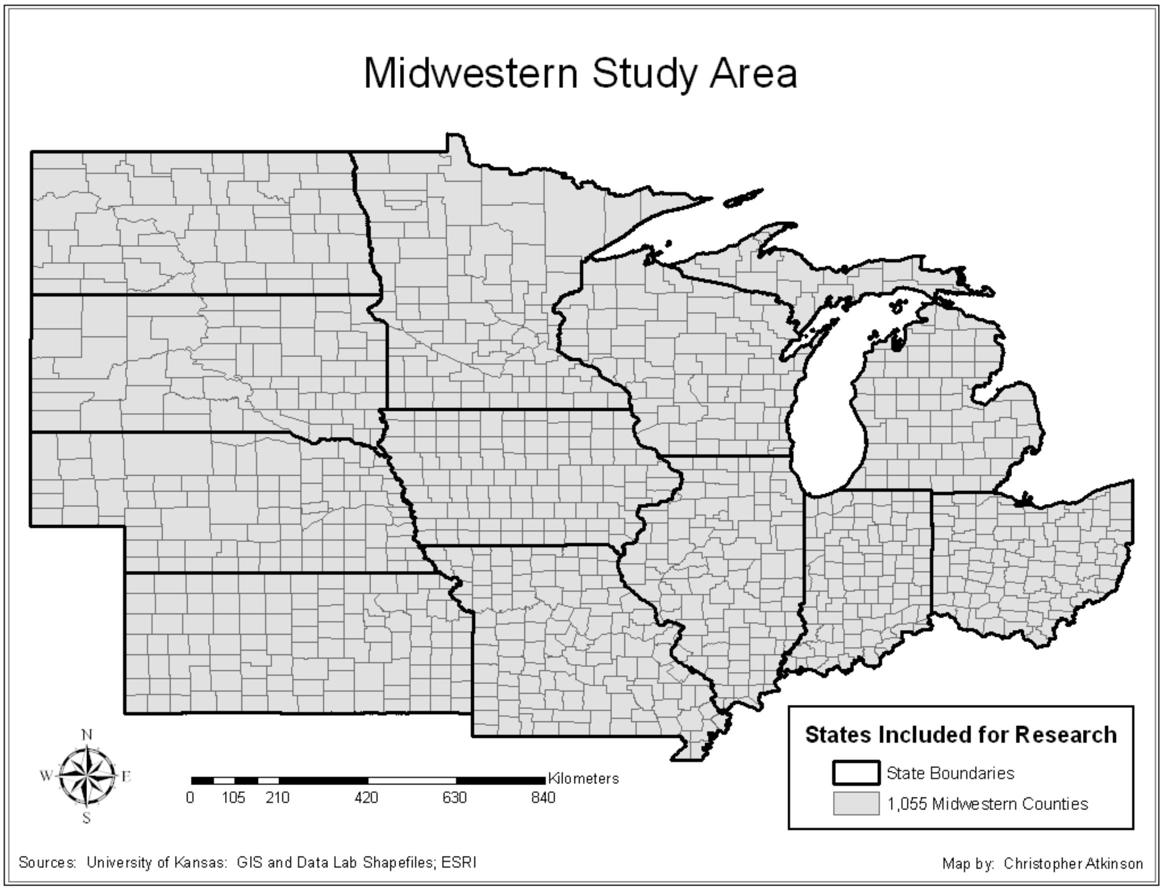


Figure 3.1. Study Area. Sources: University of Kansas: GIS and Data Lab Shapefiles; ESRI.

3.2 Definition and Identification of Extreme Midwestern Blizzards

Extreme blizzards to be included in this study were identified from two sources of weather maps. The NOAA Central Library United States Daily Weather Maps Project, 1871-2002, was used in searching for blizzards for the time period from September 1, 1966, to December 29, 2002 (surface weather map observation times: 12 AM CST for September 1, 1966 through April 14, 1968, and 6 AM CST for April 15, 1968 through December 29, 2002).

Additionally, online weather maps from the HPC Daily Weather Maps series from 2003-present was used to identify blizzards for the time period from December 30, 2002, to May 31, 2008 (surface weather maps observation time: 6 AM CST for December 30, 2002, through May 31, 2008). Following suggestions put forth by Angel and Isard (1998) in their investigation of strong extratropical cyclones traversing the Great Lakes, only blizzards with a minimum central surface pressure at or below 992 mb within the study region were included for investigation. Angel and Isard (1997) evaluated 583 extratropical cyclones traversing the Great Lakes between 1965 and 1990, and found 125 storms (~ 21.4%) with minimum central pressures at or below 992 mb. Of these 125 storms, 115 occurred during the unstable season, defined as September through April when the Lakes' water temperature is generally warmer than the ambient air overlying the Lakes (Eichenlaub 1979). Since storms over land generally do not have added instability and potential for added strengthening due to warm water, the 992 mb threshold for blizzards was deemed an appropriate threshold for this analysis. Using the Angel and Isard criteria, any blizzard crossing the 12-state study region at least once was included for analysis. Additionally, some storms over the Great Lakes at the time of observation were included if supplementary information or knowledge about the snowstorm indicated it met the required pressure threshold while over land.

Storm Data, a monthly chronicle of noteworthy weather and storm events from the NCDC in Asheville, North Carolina, and the Academic OneFile available via the University of Kansas libraries online database system was used to cross-check all storm events meeting the 992 mb criteria. There were two methods by which storm events were classified as reaching blizzard status: 1) the first method was to look for a listing of blizzard or blizzard winds in the "Character of Storm" column heading included in the *Storm Data* volumes; 2) the second possibility was to look for descriptions within the storm notes for indicators of blizzard conditions (since the "Character of Storm" label is not always obvious). For example, sometimes the "Character of Storm" listing might indicate snow or heavy snow with wind, a definite situation where reading the storm notes is necessary. In these situations, blizzard events were also identified and included when certain phrases or wind speeds provided information suggestive of probable blizzard conditions. Phrases such as "whiteout conditions", "near-whiteout conditions", "zero visibility" or "near-zero visibility" were viewed as synonymous to blizzard events. Since many severe snowstorms are described as "near-blizzards" with sustained winds not quite meeting the official blizzard definition established by the NWS (see section 2.2), the selection of blizzards for inclusion in this study also followed modified guidelines. The storm notes section in *Storm Data* occasionally provided wind speed records as an indication of blizzard events. In these cases, listings of sustained wind speeds of at least 13.4 ms^{-1} (30 mi hr^{-1}) or wind gusts of 17.9 ms^{-1} (40 mi hr^{-1}) or greater were deemed equivalent to blizzards. While this classification does not follow the official blizzard definition set forth by the NWS, this selection criteria was used to help offset any personal bias related to what constitutes an extreme winter storm. After checking all 42 years of data, the final list of storms to be included in this study included those snowstorms meeting the 992 mb minimum central pressure threshold and identified in *Storm Data* as meeting the selection criteria established for blizzards.

3.3 Charting of Blizzard Results

Several methods of visualizing the distribution of these blizzard events over time were employed. In each case, bar charts were used to show the patterns of temporal distribution. Initially, blizzard frequencies were grouped according to the two 21-year time periods. To further elucidate the temporal pattern of blizzard frequency, two other graphs were used to show the distribution of the snowstorms according to winter season and month in which they occurred.

Each winter season, defined as September through May, was grouped into three-month time periods (referred to as winter-seasonal results). Early winter was defined as September through November, mid-winter as December through February, and late winter as March through May. Blizzards that crossed over two months were credited to the month in which the storm started. Finally, a comparative monthly distribution of blizzard events was included to visually represent the changes between the two time periods on a monthly basis. The yearly, winter-seasonal, and monthly results for each time period were tallied and compared to get a sense of how extreme blizzards have changed temporally over the Midwest between September 1, 1966, and May 31, 2008.

3.4 Storm Track Re-Construction

Geographic Information Systems (GIS) spatial analysis was carried out for each extreme blizzard using ArcGIS 9.3. The main source for storm track reconstruction was the Atlas of Extratropical Storm Tracks (1961-1998) from the GISS, Columbia University. Storm track information beyond 1998 was gleaned from the NOAA Central Library, U.S. Daily Weather Maps Project (January 1, 1999 through December 29, 2002) and the HPC online weather charts for the period from December 30, 2002, through May 31, 2008. The GISS provided paths indicating the general location and orientation of the storms as they traveled through the study region. However, these track indicators were not provided in the NOAA and HPC source materials; therefore, an alternate reconstruction strategy was employed when using these additional sources. Storm tracks from the NOAA were drawn within GIS using a combination of storm position indicators (for the previous 18-24 hour period), 500 mb charts, and temperature maps. Storm tracks associated with the HPC weather maps were drawn in a similar fashion using the 500 mb charts and weather maps. Within GIS, the various tracks were converted to

TIFF format, georeferenced, rectified, and projected into an appropriate GIS coordinate system (GCS NAD 1983) before any analysis began.

3.5 Definition and Analysis of Statistical Variables for Blizzards

Spatial analysis of blizzard events utilized GIS buffering techniques and Statistical Package for the Social Sciences (SPSS) statistical analysis. GIS buffering helped identify weather stations in two sectors, a warm and cold buffer, adjacent to the individual storm tracks. In a second procedure, SPSS was used to perform a logistic regression analysis of blizzard events and their related weather data characteristics as associated with the weather stations falling within the warm and cold buffers. Weather data came from the USHCN were used to explain the influence of storm variables on federal disaster declarations in the Midwest.

3.5.1 300 km Statistical Storm Track Buffer

A GIS was used to create 300 km (186 mi) cold and warm buffers around each storm track for both time periods (January 1, 1966, through May 31, 1987, and September 1, 1987, through May 31, 2008). The cold buffer was to the north and west of each storm track, while the warm buffer flanked the south and east sides of the individual storm tracks. Figure 3.2 shows a sample representation of the 300 km cold and warm buffers flanking each side of the storm track for the Halloween Blizzard. The weather stations contained within each buffer represented the weather characteristics of that buffer as used for the statistical analysis.

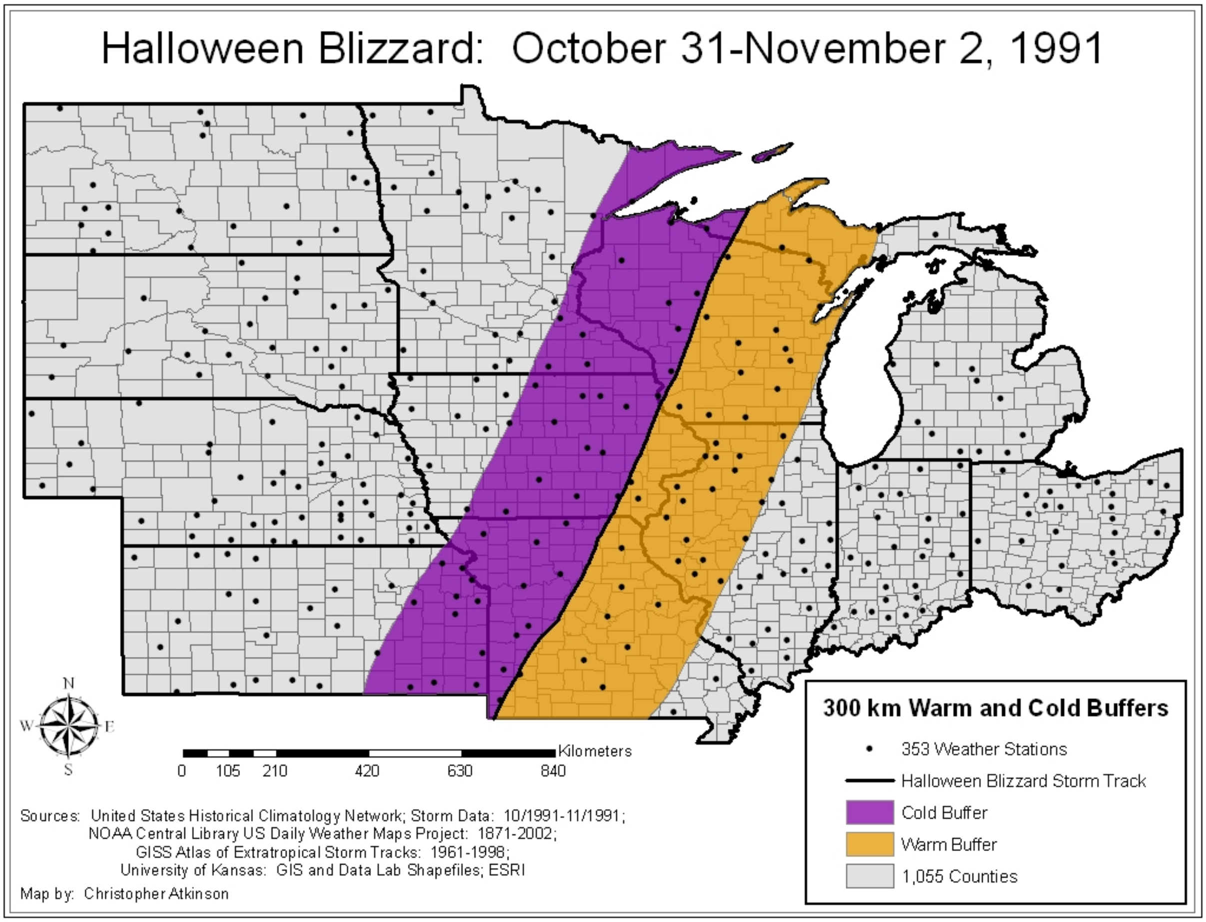


Figure 3.2. Weather Stations within Cold and Warm Buffers. Sources: USHCH; *Storm Data*: 10/1991-11/1991; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

For each storm, the weather stations identified in the cold and warm buffers and their related weather data, were used to calculate seven blizzard characteristics. These seven blizzard characteristics, or independent variables, were used to predict the likelihood of a FEDD.

3.5.2 Variable Definition for Logistic Regression Analysis

The purpose for logistic regression analysis in this study is to ascertain which blizzard characteristics accurately predict the occurrence of a FEDD, the dependent variable. Seven independent variables represented the blizzard characteristics and were used to predict the occurrence of FEDD due to extreme Midwestern blizzards: 1) SNOWFALL_COLD (defined as the highest total snowfall in centimeters within the cold buffer; 2) SNOWFALL_WARM (defined as the highest total snowfall in centimeters within the warm buffer; 3) MINIMUM TEMPERATURE_COLD, defined as the lowest minimum temperature observed during each blizzard event within the cold buffer; 4) MAXIMUM TEMPERATURE_WARM, defined as the maximum temperature observed during each blizzard event within the warm buffer; 5) MAXIMUM STORM DROP TEMPERATURE_COLD, defined as MAXIMUM TEMPERATURE_WARM minus MINIMUM TEMPERATURE_COLD; 6) ICE THRESHOLD, dummy variable defined by MAXIMUM TEMPERATURE_WARM having a value greater than -1.7° C and MINIMUM TEMPERATURE_COLD having a value less than -1.7° C; 7) MINIMUM CENTRAL PRESSURE (defined as a blizzard's lowest surface barometric pressure as indicated by daily weather maps). The ICE THRESHOLD dummy variable is intended to indicate the likelihood of icing conditions. The -1.7° C (29° F) threshold temperature used to define the ICE THRESHOLD dummy variable is based on personal communication from Dr. Richard McNulty on March 31, 2009, indicating that the most favorable surface temperature for severe icing is -1.7° C (29° F). These variables were used for a statistical comparison of the overall time period and the two sub-periods.

Logistic regression analysis was used in the analysis of extreme Midwestern blizzards. The Forward Likelihood Ratio (LR) approach was used in logistic regression analysis because it was necessary to ascertain in a stepwise fashion which meteorological variables (independent variables) of the blizzards best represented the likelihood of a federal declaration being issued.

Using the Forward LR approach of logistic regression analysis, these seven independent variables, or blizzard characteristics, were used to ascertain which weather data parameter(s) were most associated with extreme Midwestern blizzards impacts as represented by FEDD. The dependent variable in the statistical analysis was a dummy variable indicating the occurrence (or not) of a federal declaration, defined as either an emergency or disaster declaration. Each occurrence of disaster declarations was logged in the GIS on a per county basis per storm event. This method will show collective declarations for each county and state within the 12-state Midwestern region.

3.6 Mapping Spatial and Temporal Shifts in Blizzards

GIS mapping of storm tracks for the two time periods was the main method in charting spatial shifts in extreme Midwestern blizzards over time. Using the Halloween Blizzard as an example, Figure 3.3 shows the primary buffer flanking each side of the storm track out to 50 km (31 mi) indicating which counties intersect a particular storm track. Since the reanalysis done by the GIS could be prone to minor errors, the 50 km buffer was used to offset any discrepancies in this regard. After all the storm tracks were mapped in the GIS for both time periods, median storm tracks were shown and compared for Time Periods I and II to ascertain whether any shifts in position occurred.

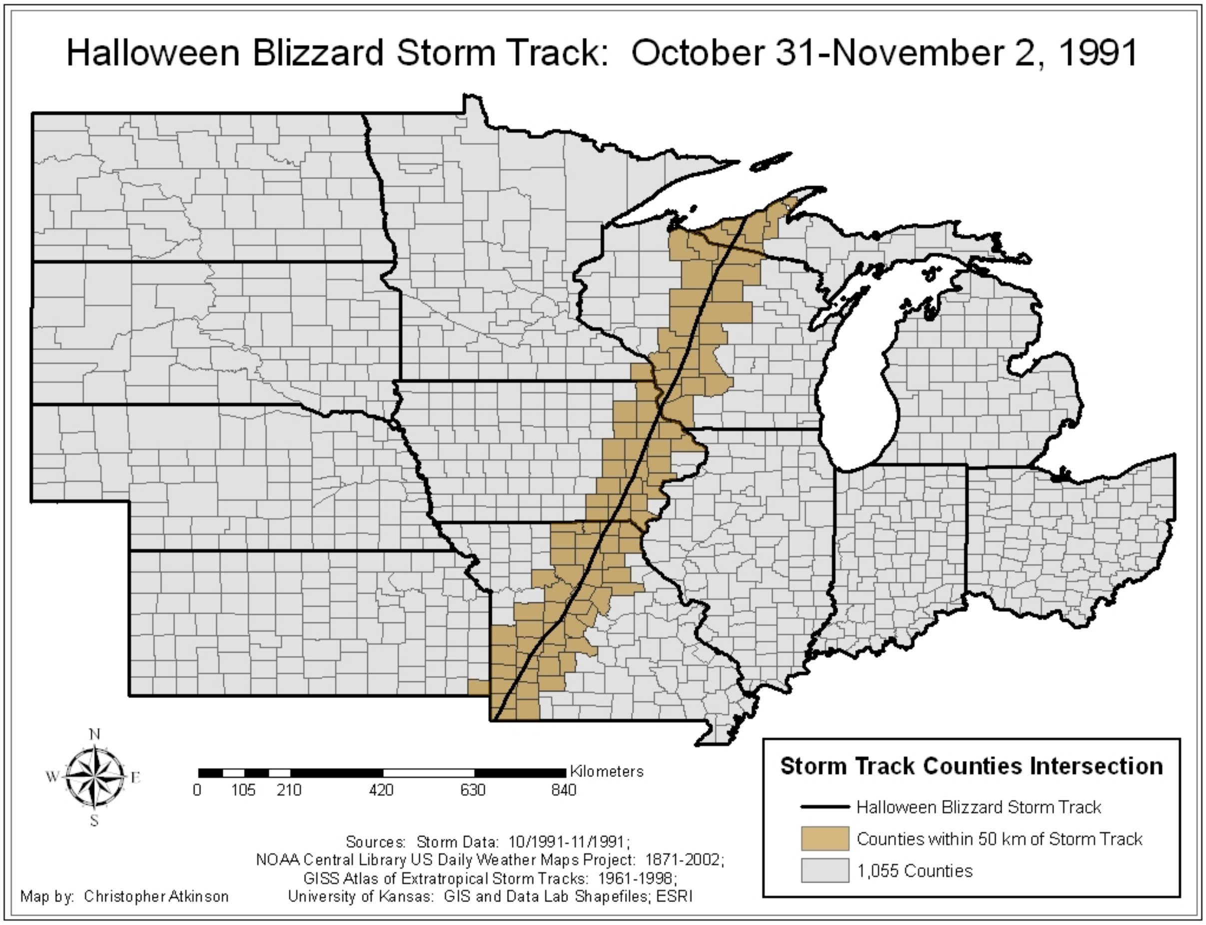


Figure 3.3. Identification of Counties within 50 km of a Storm Track. Sources: *Storm Data*: 10/1991-11/1991; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Storm track azimuth was used as a proxy for storm trajectory. Azimuth calculations were based on the latitude and longitude start and end points for each storm track. Each storm track azimuth was calculated from the inverse tangent using Pythagorean's theorem. Four classes of storm track azimuth were established by this method: 1) Class 1: 180.0°-224.9°; 2) Class 2: 225.0°-269.9°; 3) Class 3: 270.0°-314.9°; and, 4) Class 4: 315.0°-359.9°. This classification provided a better indication of storm track trajectories across the Midwest. Appendix 1 lists the latitude and longitude coordinates used in calculating each trajectory.

3.7 Identifying Federal Declaration Counties

Federal declarations, defined as either emergency or disaster declarations, were mapped using data from two sources: 1) the Public Entity Risk Institute (PERI) via the University of Delaware; and, 2) the Federal Emergency Management Agency (FEMA). Appendix 2 includes information regarding the process for selecting and identifying which counties were associated with a certain declaration. In addition to flagging the presence of a declaration using the GIS, an indication of the type of storm (snow, ice, etc.) as cause for the declaration was included for each blizzard producing a declaration. Beyond getting a sense for the spatial locations of federal declarations in time and space, this GIS analysis includes which counties/states have the most federal disaster declarations for blizzard events.

3.8 Identifying Relationships Between Blizzards and Declaration Counties

The spatial and temporal relationship between extreme Midwestern blizzards and federal declaration counties was highlighted in various ways. Using the 50 km buffer delineation of counties within storm tracks, two unclassed choropleth maps were produced showing total storm events per county for each time period. Appendix 3 explains how the county layers were updated after each storm track buffer was incorporated into the map. From this, a classed choropleth map was produced for each time period showing colorized hazard zones of impact.

County declarations were shown visually on the GIS maps by adding an overlay layer to each map representing FEDD areas for each time period. In addition, storm tracks were added to the two maps so the relationship between storm position and relative hazards, as shown by the declaration layer, could be realized.

Chapter 4: Results

4.1 Midwestern Extreme Blizzard Distribution

Between September 1, 1966, and May 31, 2008, there were 145 extreme blizzards in the Midwest. Appendix 4 lists all the blizzards included in the study.

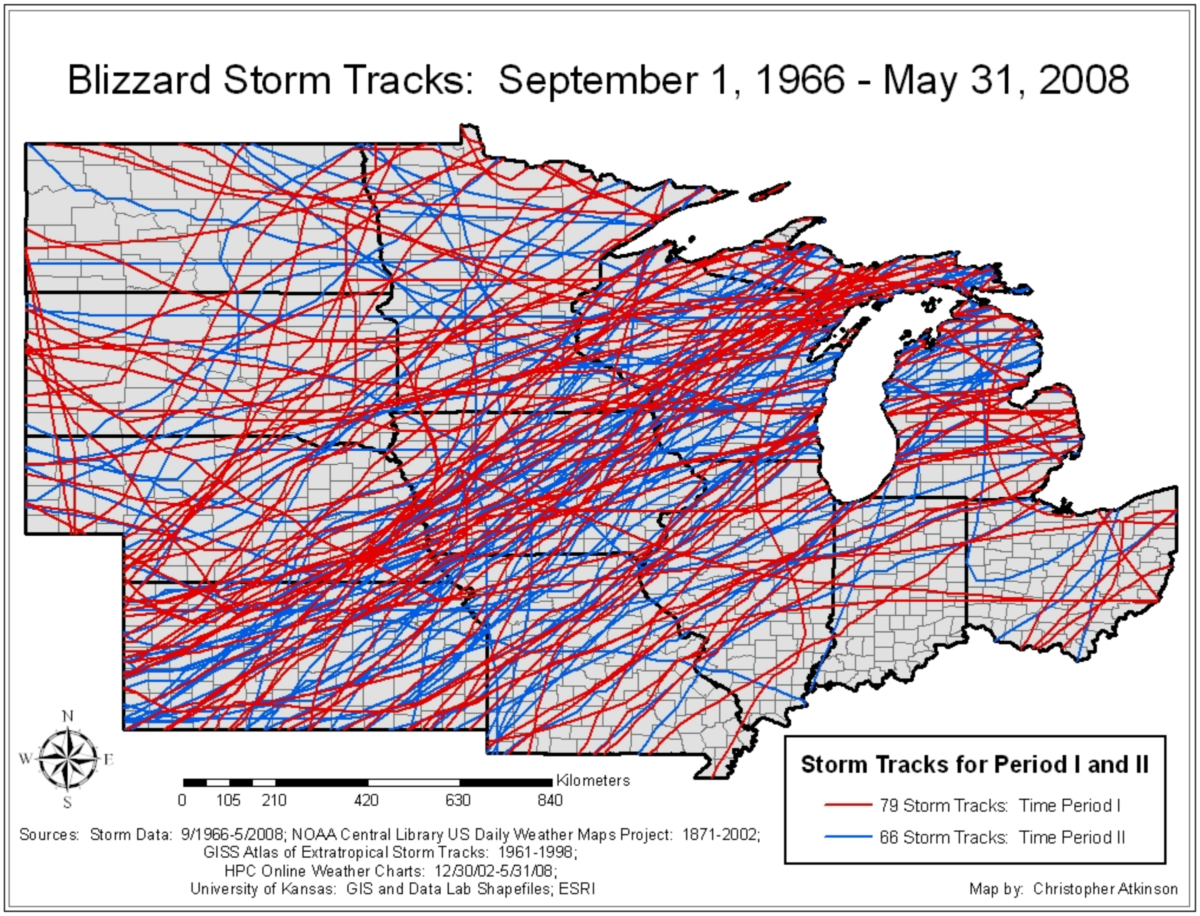
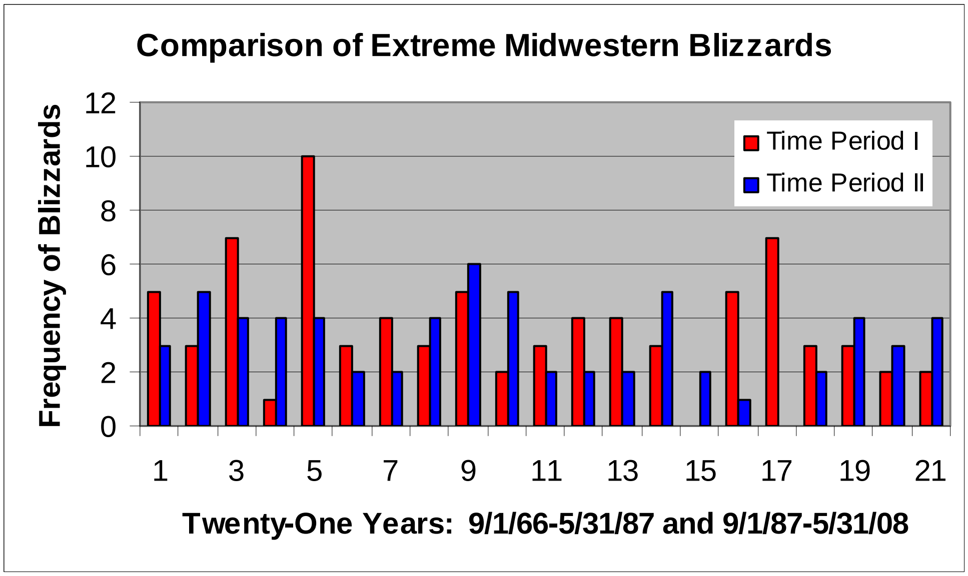


Figure 4.1. Blizzard Storm Tracks for the Overall Time Period: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

In Figure 4.1, the red lines represent the blizzard storm tracks occurring between September 1, 1966, and May 31, 1987. The blue lines in Figure 4.1 represent the blizzard storm tracks occurring between September 1, 1987, and May 31, 2008. For the overall time period, the greatest concentration of storm tracks extended from southwestern Kansas northeast to the Upper Peninsula of Michigan.

In the first time period, September 1, 1966 through May 31, 1987, there were 79 blizzards within the twelve states comprising the study region. There were 66 storms in the second time period, September 1, 1987, through May 31, 2008.



Graph 4.1. Extreme Midwestern Blizzards, Annual Frequency: September 1, 1966-May 31, 2008.
Sources: NOAA Central Library Daily Weather Maps Project, 9/1/66-12/29/02; HPC Online Weather Maps, 12/30/02-5/31/08; *Storm Data*: September, 1966- May, 2008.

Graph 4.1 displays the yearly frequencies of blizzards for each 21-year time period. Time Period I shows an average yearly frequency of 3.8 blizzards per winter season (September 1, 1966 through May 31, 1987; Graph 4.1). The winter season from September, 1970, thru May, 1971, showed the greatest number of storms with ten. Further, examination of the trends indicates a large number of Midwestern blizzards in the late 1960s thru the early 1970s with an increase in activity coming again in the early 1980s (Graph 4.1). Suggestive of this is the total winter snowfall in the Twin Cities metropolitan area for the three winters from 1981-1984: 680.7 cm (268.0 in) for an average of 226.8 cm (89.3 in) per season (NWS 2010a). In comparison, based on established 30-year benchmarks for climatology studies, the Twin Cities averaged 142.0 cm (55.9 in) of snowfall from 1971 through 2000 (Minnesota Climatology Working Group 2010a). Although it is not indicated graphically, the late 1970s produced some very snowy winters too. The worst blizzard in Ohio during the entire time period, while not part of a high-frequency winter in terms of severe blizzards, occurred on January 25-26, 1978 (Salmon and Smith 1980).

The average number of blizzards per winter season in Time Period II decreased to 3.1 snowstorms per year. The most storms occurred in the 1995-1996 winter season with seven. Like 1980-1981 in Time Period I, the 2003-2004 winter season passed with no extreme blizzards in the Midwest. In addition, approximately 52 percent of the winter seasons in the second time period experienced fewer blizzards than in Time Period I.

After testing for equality of variance, a two-tailed t test, $\alpha = 0.05$, was used to test for difference of means in blizzard frequency between Time Period I and Time Period II:

H_0: $\mu_1 = \mu_2$

H_A: $\mu_1 \neq \mu_2$

Based on the means for Period I ($\mu_1 = 3.8$ blizzards) and Period II ($\mu_2 = 3.1$ blizzards), the decrease in blizzard frequency from 79 to 66 storms was statistically insignificant, $p = 0.3016$.

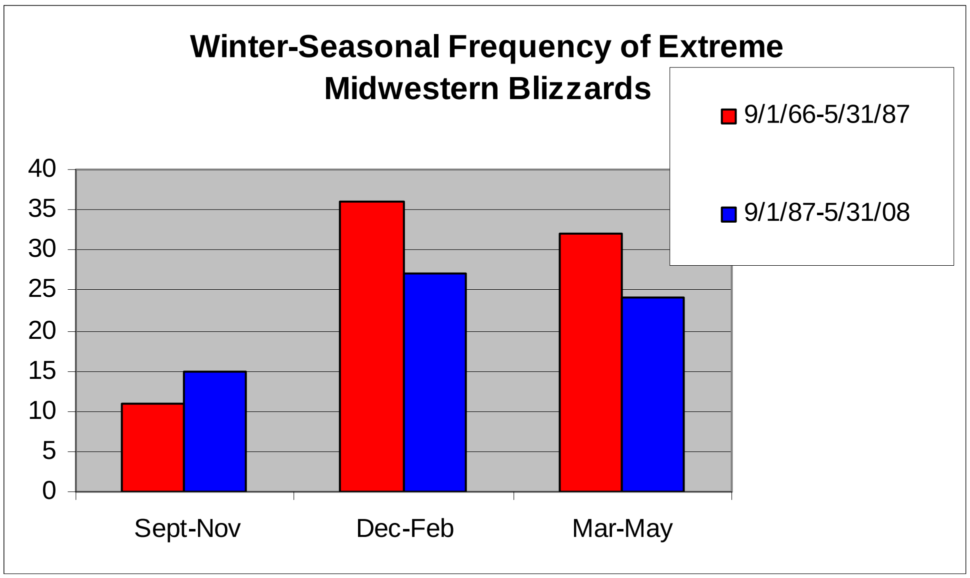
Repeating the same procedure using a two-tailed t test, $\alpha = 0.05$, the two time periods were compared using a difference of means test to ascertain any differences in blizzard intensity.

H_0: $\mu_1 = \mu_2$

H_A: $\mu_1 \neq \mu_2$

It was proven that the change in mean intensity between Time Period I ($\mu_1 = 986.0$ mb) and Time Period II ($\mu_2 = 987.6$ mb) was statistically insignificant, $p = 0.0841$. Statistically, these results seem contrary to the general storm assertions put forward by the IPCC (2007), although there clearly is a slight decrease (~ 16 percent) in storm frequency during the study period.

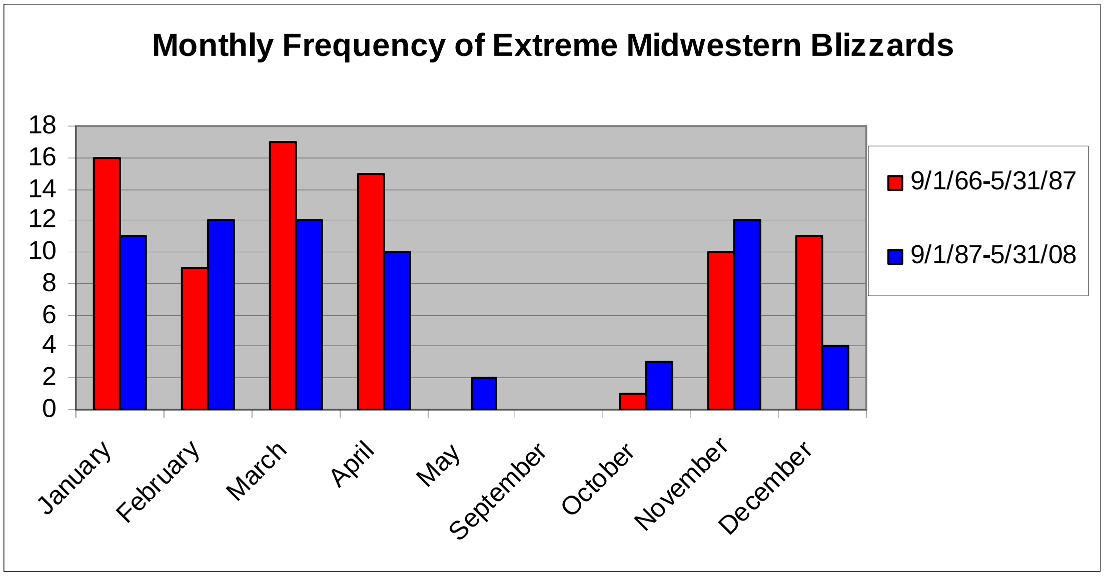
As noted previously, each time period comprised 21 winter seasons. Early winter (September-November), middle winter (December-February), and late winter (March-May), referred to as winter-seasonal results, is another way of grouping blizzards.



Graph 4.2. Winter-Seasonal Extreme Midwestern Blizzard 3-Month Frequency: September 1, 1966-May 31, 2008. Sources: NOAA Central Library Daily Weather Maps Project, 9/1/66-12/29/02; HPC Online Weather Maps, 12/30/02-5/31/08; *Storm Data*: September, 1966- May, 2008.

Graph 4.2 shows that all three set of winter-seasonal results show changes in the frequency of blizzards. Overall, the greatest number of storms occurred in middle winter between December and February followed closely by the March through May time period. In contrast to declines in the number of snowstorms during in middle and late winter, Time Period II between September and November saw a 36.4 percent growth in the number of blizzards. During the second time period, decreases in the frequency of storms in the middle (36 to 27) and late (32 to 24) winter accounted for decreases of 25 percent in both cases. The overall trend suggests an increase in early storm events combined with an overall decline in the total number of storms over the duration of the study period.

The winter-seasonal frequency of extreme Midwestern blizzards was classified according to monthly frequency. Most extreme Midwestern blizzards developed between January and May, although November stands out as a secondary high point in early winter.



Graph 4.3. Extreme Midwestern Blizzards, Monthly Frequency: September 1, 1966-May 31, 2008. Sources: NOAA Central Library Daily Weather Maps Project, 9/1/66-12/29/02; HPC Online Weather Maps, 12/30/02-5/31/08; *Storm Data*: September, 1966- May, 2008.

Graph 4.3 indicates the overall decline in blizzards in Time Period II; the frequency of extreme blizzards in the Midwest decreased approximately 16 percent between the two time periods. The top three months in total number of storms are January, March, and April. Using the Mann Whitney U test, $\alpha = 0.05$, none of the changes in monthly blizzard frequencies were statistically significant during the nine-month winter season (Table 4.1).

Month	Period I	Period II	Total Storms	P value
September	0	0	0	1.000
October	1	3	4	0.299
November	10	12	22	0.797
December	11	4	15	0.397
January	16	11	27	0.442
February	9	12	21	0.149
March	17	12	29	0.347
April	15	10	25	0.275
May	0	2	2	0.152
Total	79	66	145	0.302

Table 4.1. Percentage Change in the Monthly Distribution of Extreme Midwestern Blizzards: September 1, 1966-May 31, 2008. Sources: NOAA Central Library Daily Weather Maps Project, 9/1/66-12/29/02; HPC Online Weather Maps, 12/30/02-5/31/08; *Storm Data*: September, 1966-May, 2008.

4.2 Statistics of Extreme Midwestern Blizzards

Logistic regression analyses were run on the first (79 storms) and second (66 storms) time periods in the attempt to ascertain which meteorological characteristics, as indicated by the independent variables described in the methodology section, led to the occurrence of federal emergency or disaster declarations. Since all values for ICE THRESHOLD, a categorical independent variable, were equal to 1, indicating all blizzard temperature profiles passed the -1.7° C (29° F) threshold, blizzard azimuth was substituted as the final independent variable used in the logistic regression analysis. For both periods, there were some moderate correlations in the independent variables used to define the blizzards; however this was not deemed detrimental to the analysis (Table 4.2).

	SNOW	SNOW	MIN	MAX	STORM	MIN	AZIMUTH
	COLD	WARM	TEMP	TEMP	DROP	CENT	
			COLD	WARM	TEMP	PRESS	
SNOWFALL COLD	1.000	0.532	-0.449	-0.263	0.223	-0.084	-0.174
SNOWFALL WARM	0.532	1.000	-0.549	-0.343	0.248	0.024	0.042
MIN TEMP COLD	-0.449	-0.549	1.000	0.597	-0.484	0.031	-0.360
MAX TEMP WARM	-0.263	-0.343	0.597	1.000	0.413	0.084	-0.362
STORM DROP TEMP	0.223	0.248	-0.484	0.413	1.000	0.056	0.013
MIN CENTRAL PRES	-0.084	0.024	0.031	0.084	0.056	1.000	0.159
AZIMUTH	-0.174	0.042	-0.360	-0.362	0.013	0.159	1.000

Table 4.2. Independent Variable Bivariate Correlations. Source: Adapted from SPSS Output.

Ideally, the R values shown in Table 4.2 would be at or near R = 0.000 for most pairs of independent variables; however, the R values shown are acceptable since the highest indices indicate only moderate positive and negative correlations. The three highest correlations exist between (all significant at $\alpha = 0.01$): 1) absolute maximum temperature in the warm buffer and absolute minimum temperature in the cold buffer (0.597); 2) the absolute minimum temperature in the cold buffer and highest total station snowfall in the warm buffer (-0.549); and, 3) the highest total station snowfall in the warm buffer and the highest total station snowfall in the cold buffer (0.532). As related to the other independent variables, minimum central pressure and azimuth indicate minimal positive and negative correlations.

4.2.1 Logistic Regression Analysis for Time Period I: 79 Blizzards

Time Period I showed no concerns regarding multicollinearity of independent invariables. Tolerance values ranged from 0.427 to 0.942 with variance inflation factor (VIF) indicating a range from 1.062 to 2.339.

The model equation used the Forward LR approach with independent variables entering the model at $\alpha = 0.10$ and removal set at $\alpha = 0.15$. The model for the 79 blizzards in Time Period I ran two steps with minimum central pressure (Prob. value = 0.059) and absolute maximum temperature in the warm buffer (Prob. value = 0.070) entering the model on two iterations.

Step 1 Model Equation:

Federal Declaration = $-0.096(X_1) + 91.821$

Where X_1 = Minimum central pressure

For minimum central pressure, $R^2 = 0.086$, and would be significant at $\alpha = 0.10$ (Prob. value = 0.090). Step 1 of the model equation failed to improve the predictive capacity of the constant, remaining at 92.4 percent correct.

Step 2 Model Equation:

Federal Declaration = $-0.099(X_1) - 0.091(X_2) + 88.647$

Where X_1 = Absolute maximum temperature in the warm buffer

Where X_2 = Minimum central pressure

Adding absolute maximum temperature in the warm buffer increased R^2 to 0.169, again significant at $\alpha = 0.10$ level (Prob. value = 0.089). Step 2 of the model equation only slightly improved the predictive capacity of the constant to 93.7 percent.

4.2.2 Logistic Regression Analysis for Time Period II: 66 Blizzards

Time Period II showed no concerns regarding multicollinearity of independent invariables. Tolerance values ranged from 0.577 to 0.857 with VIF indicating a range from 1.167 to 1.733.

The model equation used the Forward LR approach with independent variables entering the model at $\alpha = 0.10$ and removal set at $\alpha = 0.15$. The model for the 66 blizzards in Time Period II terminated after the constant entered the equation because all prob. values exceeded $\alpha = 0.10$. The lowest prob. value for entrance into the model equation was 0.108 (independent variable: azimuth). The independent variables in both models performed very poorly in predicting the occurrence of federal declarations due to extreme Midwestern blizzards.

4.3 Blizzard Storm Tracks for Time Period I (September 1, 1966-May 31, 1987)

The predominate direction for blizzard storm tracks in Time Period I indicated a southwest to northeast trajectory. The latitude and longitude coordinates support this (Table 4.3).

LONG Start Point	LONG End Point	LAT Start Point	LAT End Point
-102.026	-84.857	38.779	46.433

Table 4.3. Median Longitude and Latitude Starting and Ending Points for Time Period I. Source: Adapted from ArcGIS Output.

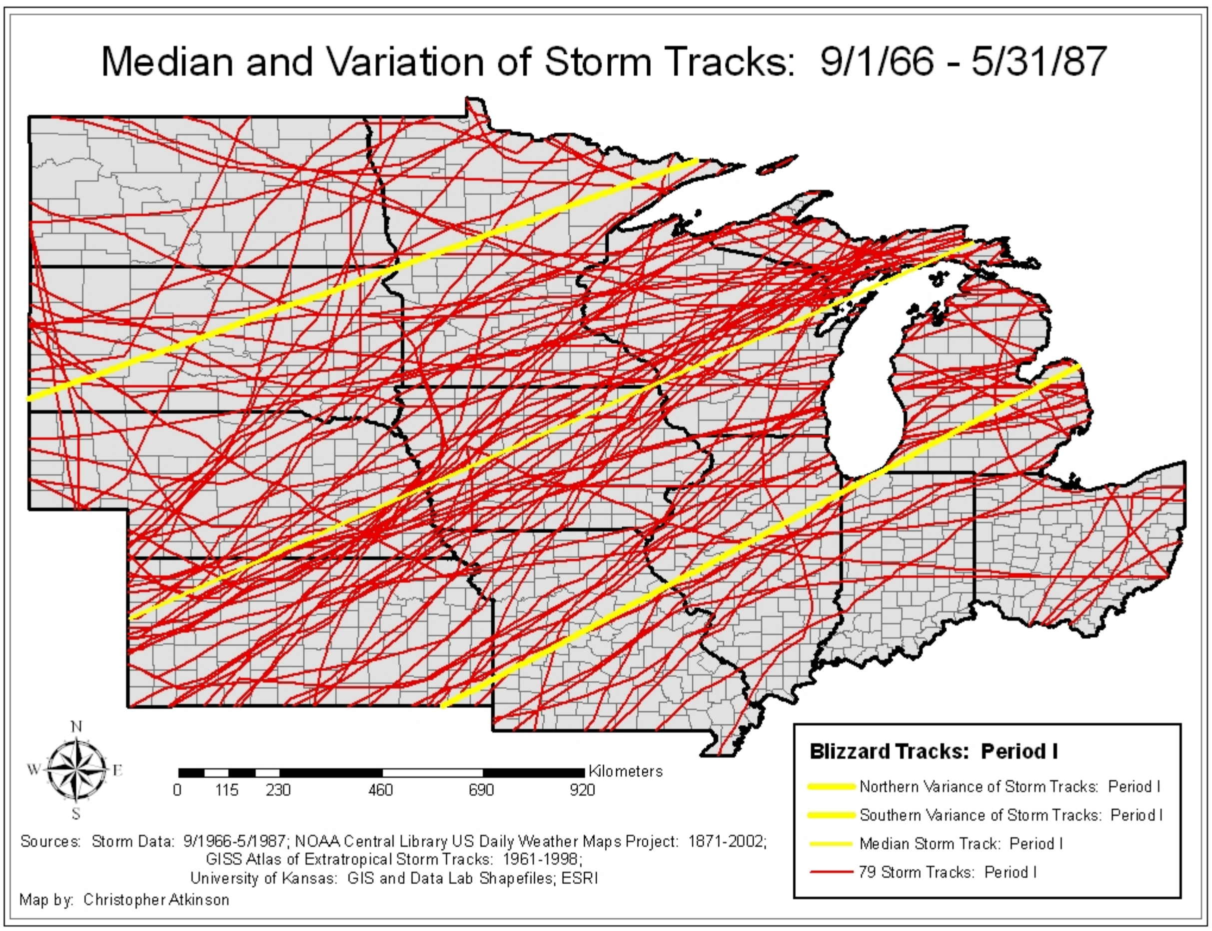


Figure 4.2. Time Period I Storm Tracks: Median and Variance. Sources: *Storm Data*: 9/1966-5/1987; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Figure 4.2 shows all 79 storm tracks for Time Period I along with the median track in yellow and the average variance of these tracks. The wider yellow lines to the north and south of the median track indicate the variance in the 79 tracks for Time Period I based on calculating the median value of the storm starting and ending points from the median storm track. The median azimuth direction for the 79 blizzards occurring between September 1, 1966 and May 31, 1987 was 246.0 degrees. The variation in storm tracks converge near Green Bay and the Upper Peninsula of Michigan with less spatial variation in storm tracks near the termini.

4.4 Blizzard Storm Tracks for Time Period II (September 1, 1987-May 31, 2008)

The blizzard storm tracks in Time Period II, when compared to Time Period I, changed spatially across the study region. Two items are noted from time period II: 1) the median storm track has shifted south; and, 2) the end point termini (northern and southern variance of storm tracks) are closer together compared to time period I (Table 4.4).

LONG Start Pt	LONG End Pt	LAT Start Pt	LAT End Pt
-102.026	-84.3525	37.928	46.1545

Table 4.4. Median Longitude and Latitude Starting and Ending Points for Time Period II. Adapted from ArcGIS Output.

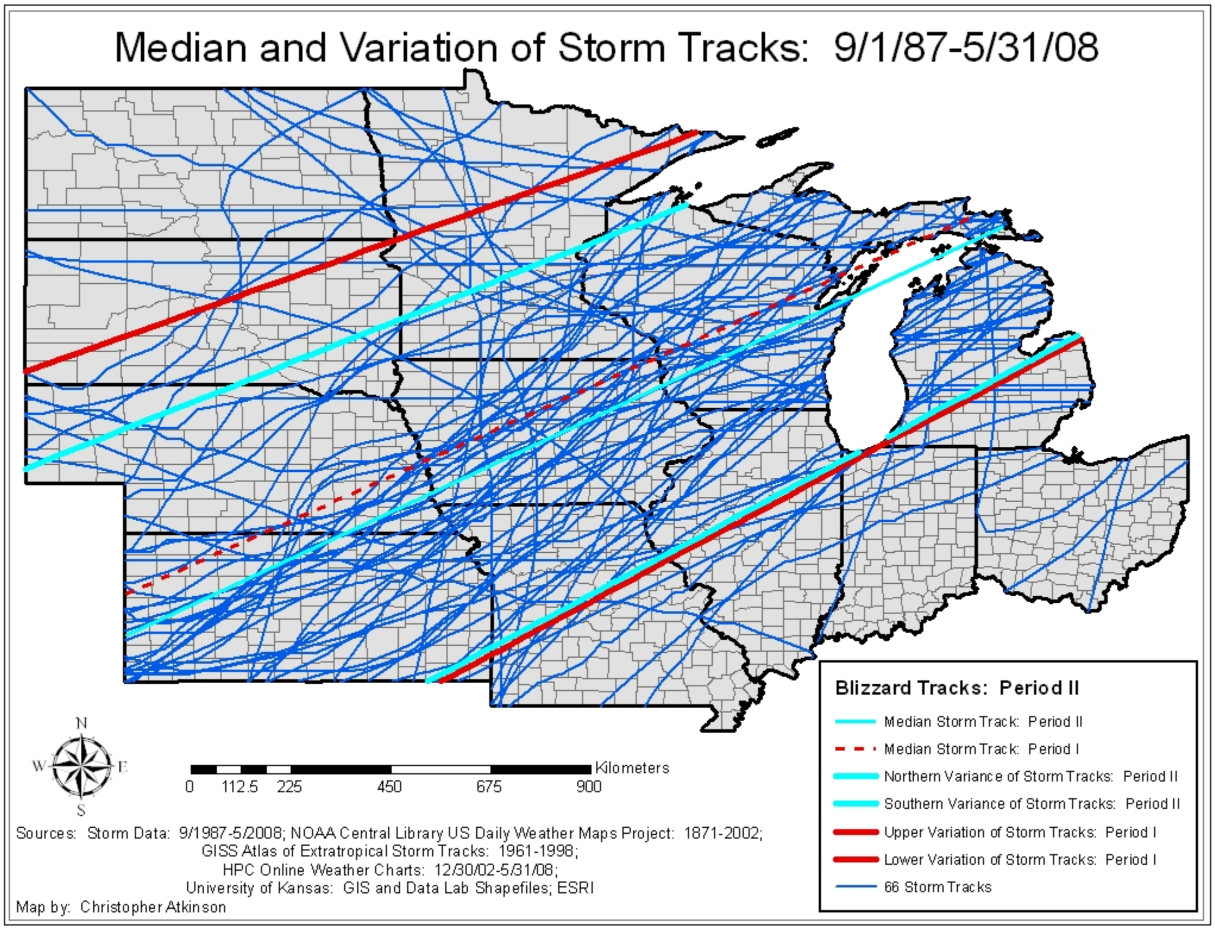


Figure 4.3. Time Period II Storm Tracks: Median and Variance. Sources: *Storm Data*: 9/1987-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Figure 4.3 shows all 66 storm tracks and storm track variation for Time Period II along with the median track shown in cyan. As indicated visually in the map above, the median azimuth direction for the 66 blizzards occurring between September 1, 1987 and May 31, 2008 was 245.0 degrees with the dashed red line showing the median storm track from Time Period I; the median storm track in Time Period II shifted about two counties or 100 km (62 mi) to the south. Statistically, this slight southward shift was shown to be insignificant using a two-tailed t test with $\alpha = 0.05$, $p = 0.508$. As during Time Period I using the method of displaying variance based on the latitude and longitude start and end points, there was less spatial variation in blizzard storm tracks during Time Period II. When comparing the latitudinal shift in start and end point storm track variation between Time Periods I and II, the changes were found to be statistically insignificant assuming equality of variances using Levene's test (Table 4.5).

Change in Latitude	Equality of Variance	Equality of Means
Start Point	0.874	0.460
End Point	0.848	0.165

Table 4.5. Statistical Test for Equality of Means for Median Variation in Latitude Start and End Points: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

4.5 Spatial Relationship of Blizzard Hazards: Time Period I and Time Period II

Counts of blizzard occurrence by county based on the number of 50 km (31 mi) storm track buffer overlays (frequency of county intersections) mimic the median storm track shown in Figure 4.2.

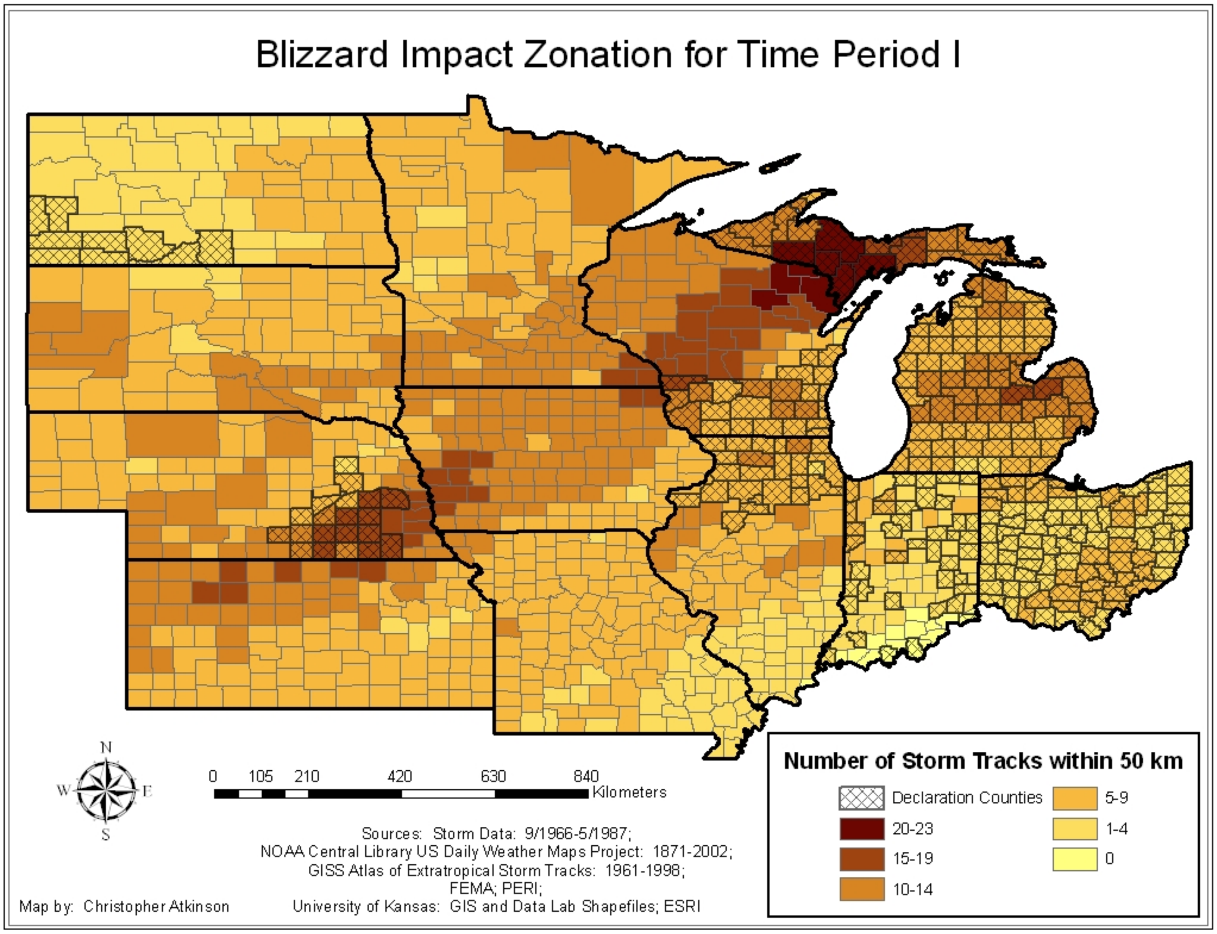


Figure 4.4. Blizzard Hazard Counties for Time Period I: September 1, 1966-May 31, 1987. Sources: *Storm Data*: 9/1966-5/1987; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; FEMA; PERI; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Figure 4.4 indicates the primary region, (20 to 23 storm track intersections), was located in northeastern Wisconsin and the central portion of the Upper Peninsula of Michigan. In addition, two secondary regions of storm track intersections (15 to 19 storms) stretched from north-central Kansas to west-central Iowa and from extreme northeastern Iowa through the central portions of Wisconsin. The highest frequency of blizzard hazards (those counties stretching from northeastern Wisconsin through the central portion of Michigan) were located slightly north of the median storm track: about 100 km (62 mi) at the western end of the study area and around 200 km (124 mi) on the eastern end. The probability of a storm track traveling directly through certain counties decreases rapidly to the northwest or southeast of the primary or secondary intersection areas. As expected, there is a positive correlation between the primary and secondary storm intersection counties and the median storm track for Time Period I (Figure 4.2).

Figure 4.4 also shows the federally-declared counties (288 counties in Time Period I) with at least one federal declaration. These counties appear with a cross-hatch pattern on the map. The most populous counties in the study region were located mostly east of 92 degrees west longitude, so some storms severely impacted those counties. Interestingly, one snowstorm (the January 26, 1978 blizzard) created major weather impacts for all 83 counties in Michigan and 88 counties in Ohio. In contrast, only 20 counties in Nebraska and 9 counties in North Dakota experienced declarations during Time Period I.

During Time Period II, there was a decrease in the number of storm track intersections and an increase in the number of federally-declared counties. Even though the number of storm track intersections decreased, the total number of federal declarations more than doubled.

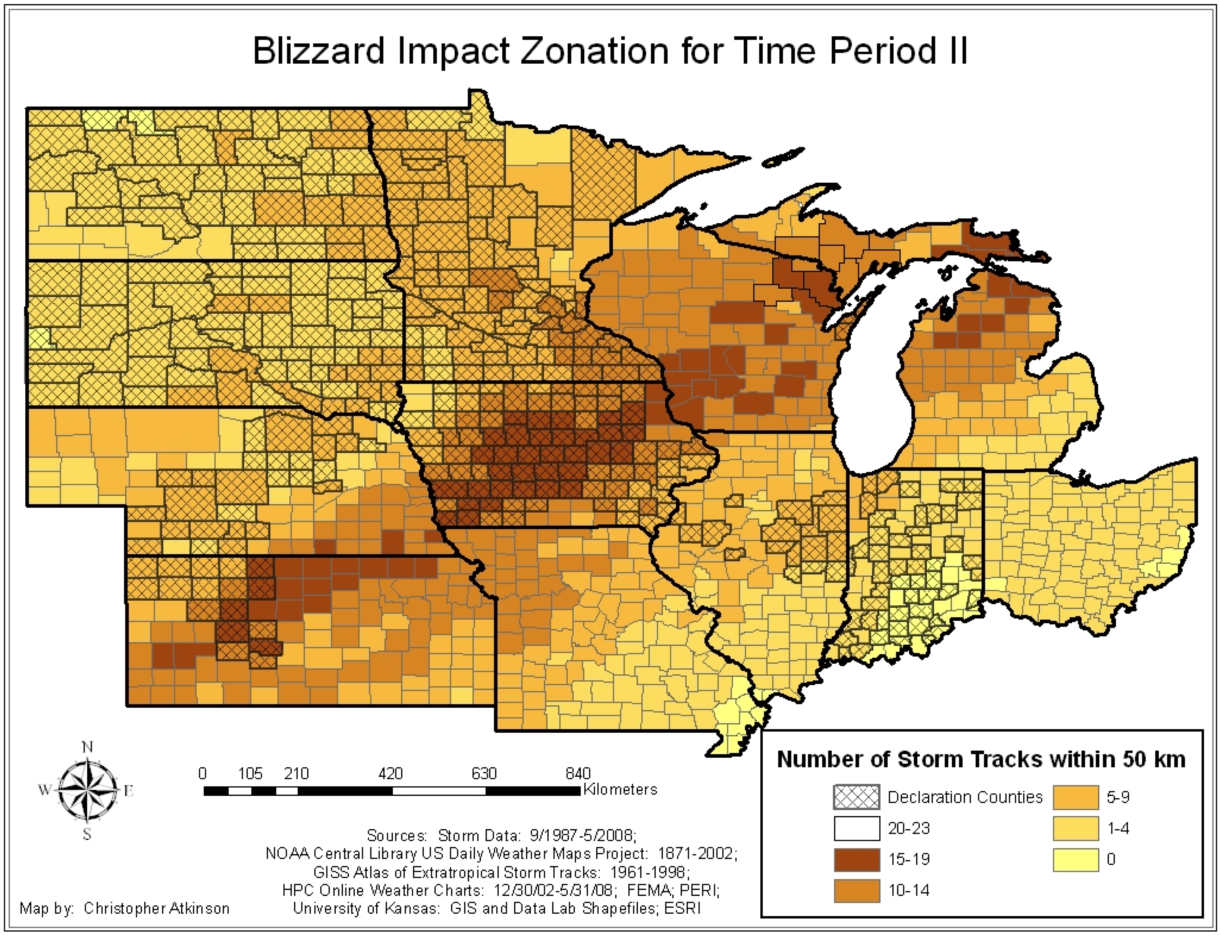


Figure 4.5. Blizzard Hazard Counties for Time Period II: September 1, 1987-May 31, 2008. Sources: *Storm Data*: 9/1987-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

In Time Period II, blizzards maintained the common southwest to northeast storm track trajectory common to Kansas low pressure systems originating in the middle Rocky Mountains before moving east into the Central High Plains. Even though there were some similarities between the two periods in terms of cyclogenesis region and trajectory of movement, there were also some differences in frequency and position of the storm track intersections during Time Period II. In terms of storm class intersections, the frequency of counties within 50 km (31 mi) of tracks dropped in Time Period II: Figure 4.5 shows the absence of the top classification (20 to 23 storm track intersections) that was present in Time Period I. Fewer blizzards (66 in Period II versus 79 in Period I) could account for the decrease in storm trajectories during Time Period II. In addition to changing frequency in the number of storm track intersections in Figure 4.5, the core area of counties most affected by these blizzards shifted south and west from the Upper Peninsula of Michigan and portions of Wisconsin to three counties in Iowa.

In similar fashion to Time Period I, Figure 4.5 also shows the federally declared counties occurring during Time Period II with a cross-hatch pattern. Most of the declared counties for Time Period II are located north and west of the median storm track. All of the counties in South Dakota and North Dakota saw presidential declarations sometime during Time Period II.

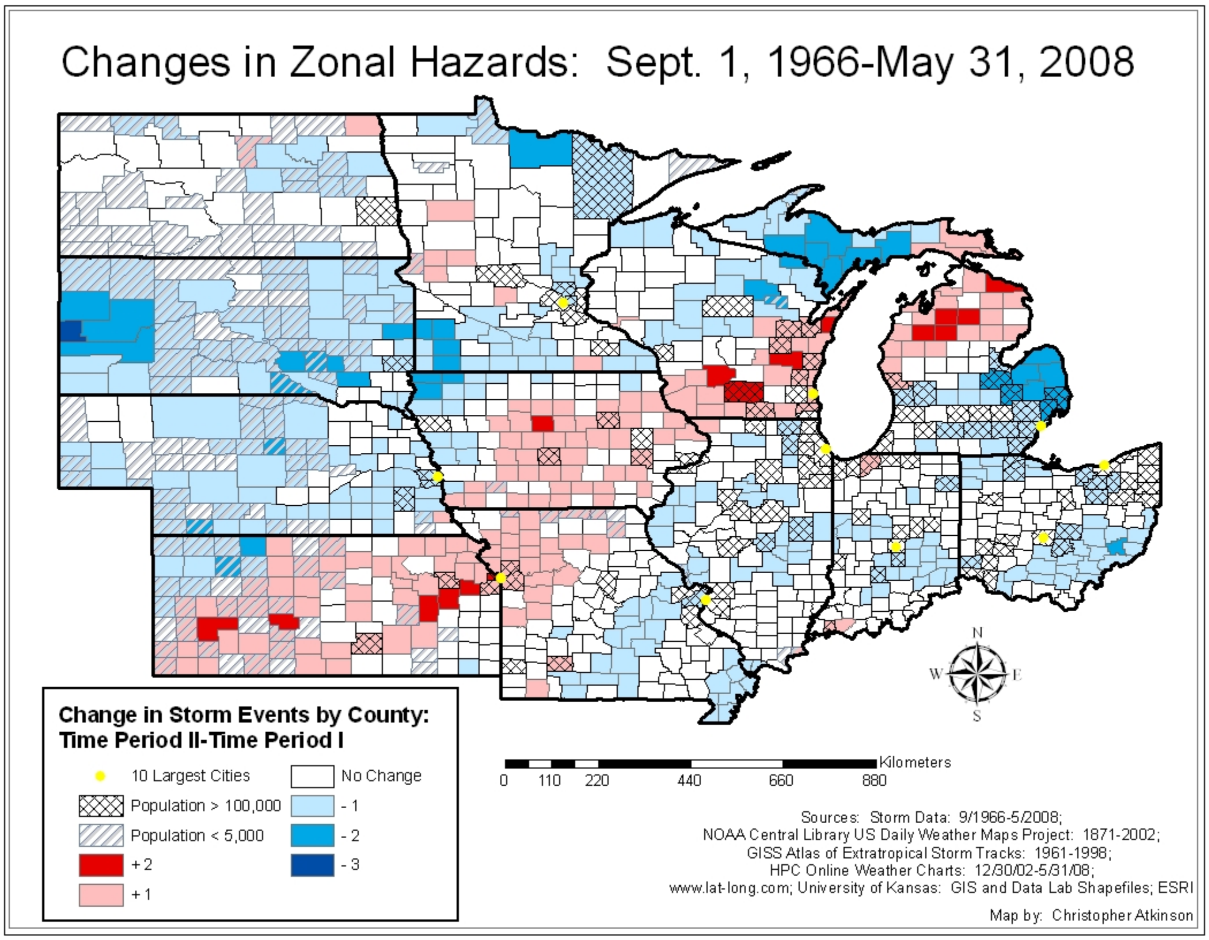


Figure 4.6. Changes in Extreme Blizzard Storm Track Frequency per County: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

The map in Figure 4.6 shows the change in storm frequency, defined as the difference in county blizzard storm track frequencies between Time Period II and Time Period I. The red and pink colorations on the map indicate greater storm track frequencies for Time Period II versus Time Period I, while the dark and light blue colorations indicate less frequency of blizzard storm tracks occurring in Time Period II as compared to Time Period I. The greatest concentration of blizzards was along the center of the tracks with fewer storms to the north and south of this main trajectory.

While not stated explicitly in the research hypotheses, a consideration of population patterns in the study region is important in the context of blizzard impacts. Figure 4.6 shows county populations greater than 100,000 residents including the ten largest cities of Cleveland, Columbus, Indianapolis, Detroit, Chicago, Milwaukee, St. Louis, Kansas City, Omaha and Minneapolis. Other regional centers in the northern and western regions of the study area also have county populations exceeding 100,000 residents. Places like Fargo, Duluth, Sioux Falls, Sioux City, Lincoln, Topeka, and Wichita are included in this group. Midwestern blizzards cause a larger degree of damage and loss in urban areas because capital investment and infrastructure is much greater in these areas versus the less populated, largely rural regions of the Great Plains. When compared to sparsely-populated rural regions in the western part of the study area, urban areas do not require large-magnitude blizzards to inflict similar levels of loss and damage.

4.6 Federal Declaration Counties

In all, twenty-three blizzards during the study period resulted in FEDD. Counties with declared FEDD showed significant differences in their spatial distributions (Figures 4.4 and 4.5).

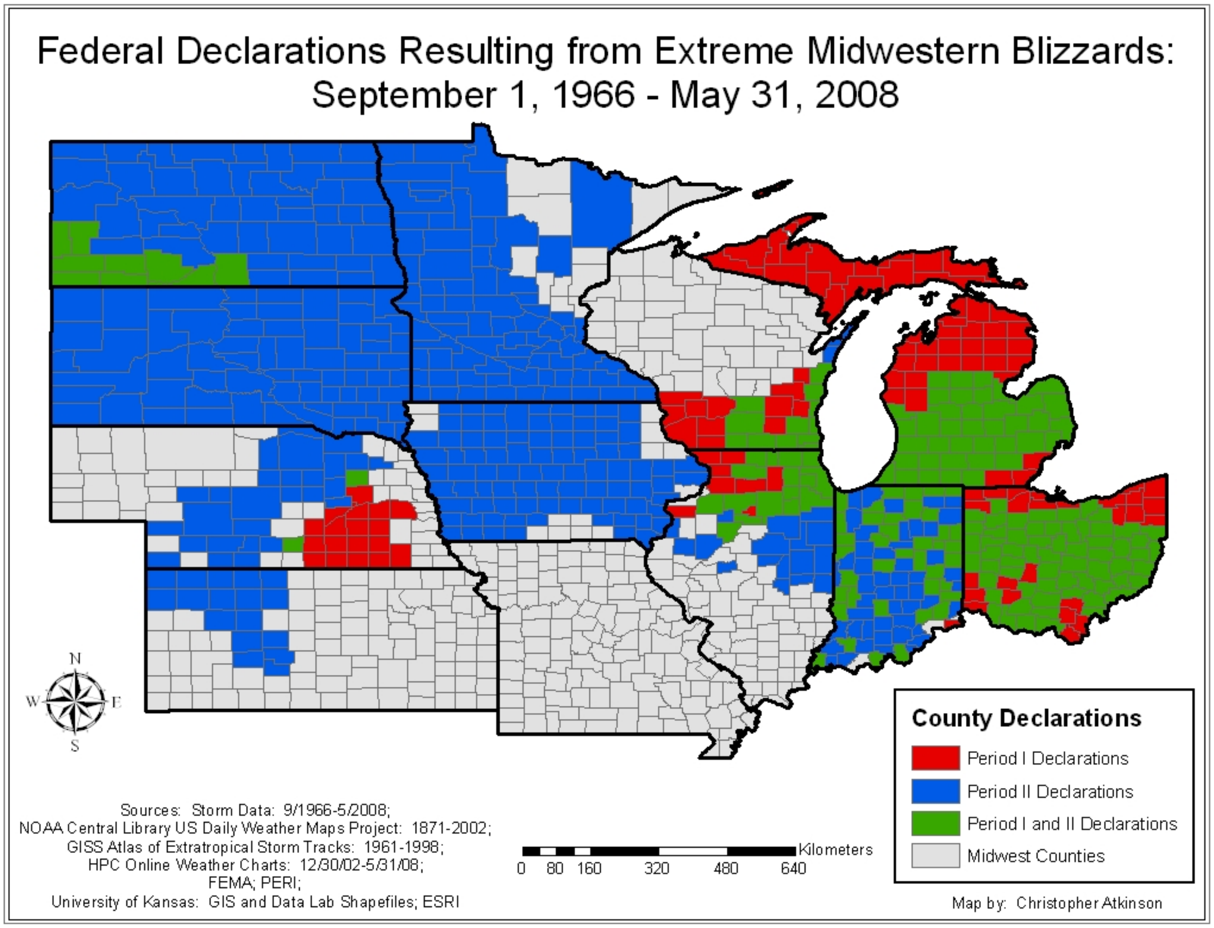


Figure 4.7. Presidential Emergency and Disaster Declarations: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Figure 4.7 shows the location and number of FEDD occurring during Time Period I and II. Comparing the spatial patterns in FEDD (Figure 4.7), county declarations for Time Period I largely occurred in the eastern portion of the study region. The only exception to this is a small grouping of counties clustered in south-central Nebraska. County declarations in Time Period II were found mainly in the northern and western portions of the study region. Door County, Wisconsin, along with a large grouping of counties in Illinois and Indiana are the exceptions to this general pattern. Figure 4.7 also shows most of the common declarations, those counties declared in both time periods, centered in the eastern portion of the study region. Only two counties in Nebraska and nine counties in North Dakota break this pattern. This map also shows all the counties with at least one federal declaration occurring sometime between September 1, 1966, and May 31, 2008, but it does not show multiple declarations for a single county. In both time periods, multiple storms during the same year, storms crossing over the same areas during one of the periods, or subsequent effects (such as unrealized damages) due to a previous storm sometimes produced more than one declaration for certain counties (Table 4.6).

State	Period I Declarations	Period II Declarations	Common Declarations	Total
Illinois	7	15	19	41
Indiana	0	48	41	89
Iowa	0	86	0	86
Kansas	0	17	0	17
Michigan	44	0	39	83
Minnesota	0	76	0	76
Missouri	0	0	0	0
Nebraska	18	27	2	47
North Dakota	0	44	9	53
Ohio	26	0	62	88
South Dakota	0	66	0	66
Wisconsin	12	1	13	26
Total	107	380	185	672

Table 4.6. Period I, Period II, and Common Federal Declarations: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Table 4.6 shows the delineation of the 672 counties receiving federal declarations during the 42-year study as displayed in Figure 4.7. The table breaks down the number of declarations due to extreme Midwestern blizzards according to time period and the number of counties receiving declarations. It is important to realize that the total number of counties (right column in Table 4.6) match the percentages given in Table 4.7. For example, forty-one counties in Illinois received declarations between September 1, 1966, and May 31, 2008. Illinois has a total of 102 counties, so (41/102)*100 = 40.2 percent, matching the value given in Table 4.7.

State	Federal Emergency and Disaster Declarations (FEDD)	Storms with FEDD: Period I	Storms with FEDD: Period 2	Percentage of Counties with FEDD (Number of Counties in State)
Illinois	3	1	2	40.2 (102)
Indiana	6	2	4	96.7 (92)
Iowa	4	0	4	86.9 (99)
Kansas	1	0	1	16.2 (105)
Michigan	4	3	1	100 (83)
Minnesota	6	0	6	87.4 (87)
Missouri	0	0	0	0 (115)
Nebraska	2	1	1	50.5 (93)
North Dakota	7	2	5	100 (53)
Ohio	3	2	1	100 (88)
South Dakota	9	0	9	100 (66)
Wisconsin	3	2	1	36.1 (72)
Totals	48	13	35	63.7 (1055)

Table 4.7. State and County Federal Declarations Resulting from 23 Extreme Midwestern Blizzards: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; PERI; FEMA; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Table 4.7 shows that occasionally one blizzard produced more than one federal declaration as it traveled through the study region, since the total number of federal declarations is more than double the actual number of declaration-producing blizzards (48 declarations versus 23 blizzards). All counties in Michigan, Ohio, North Dakota, and South Dakota experienced declarations sometime during the 42-year time period. Missouri was the only state to not experience any federal declarations during this time span. In addition, Time Period II saw a 169.2 percent increase in the number storms with FEDD (13 vs. 35 declarations). Stated another way, of 48 declarations resulting from 23 extreme Midwestern blizzards, 35 of those 48 declarations (72.9 percent) occurred during Time Period II. Finally, the right column in Table 4.7 indicates the percentage of federally-declared counties in each of the twelve states. A total of 672 counties (63.7 percent) received declarations sometime during the 42-year study.

Of the 672 counties receiving federal declarations of need sometime during the 42-year study, Table 4.8 indicates that three states saw declines in the total number of federal declarations and eight increased in the total number of declared counties. Missouri remained unchanged (it had declarations during the study; however these hazards were generally due to ice storms). A complete listing of all declared counties per blizzard is located in Appendix 5.

State	Total Number of County Declarations: Period I	Total Number of County Declarations: Period II	p value
Illinois	24	37	0.554
Indiana	41	150	0.363
Iowa	0	136	0.076
Kansas	0	17	0.317
Michigan	124	39	0.311
Minnesota	0	151	0.038
Missouri	0	0	1.000
Nebraska	20	29	0.973
North Dakota	9	119	0.300
Ohio	135	62	0.554
South Dakota	0	219	0.019
Wisconsin	25	14	0.554
Totals	378	973	NA

Table 4.8. Total Number of County Declarations per State and Time Period: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; PERI; FEMA; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Table 4.8 shows the total number of county declarations for each of the 21-year time periods. Keep in mind that the total number of county declarations indicates the possibility of one storm producing multiple declarations for the same county or multiple declarations within the same winter season from different storms (compare to Table 4.6). These reasons account for the differences between Periods I and II. There is a significant increase in the total number of county declarations (973 versus 378) in Time Period II compared to Period I, an increase of 157.4 percent. Each of the 23 extreme Midwestern blizzards created wintertime hazards as a result of snow, ice, or mixed snow and ice precipitation.

Table 4.9 notes each of the 23 blizzards resulting in presidential emergency or disaster declarations in the Midwest from September 1, 1966 through May 31, 2008. The chart also lists the winter-weather hazard leading to the declaration along with an estimate of monetary damages.

Blizzard	Storm Hazard Causing Declaration	Monetary Damage Estimate (2008 US Dollars)
March 19-20, 1976	Ice	131,954,883
January 26-28, 1977	Snow	Data Not Available
November 8-10, 1977	Snow	Data Not Available
November 19-21, 1977	Snow	Data Not Available
January 26, 1978	Snow	Data Not Available
January 13-14, 1979	Snow	Data Not Available
January 24-25, 1990	Ice	9,297,012
March 11-13, 1991	Ice	33,389,453
October 31-November 2, 1991	Ice	34,415,203
November 17-18, 1994*	Snow and Ice	1,922,653
November 27-28, 1994*	Snow and Ice	1,922,653
November 26-27, 1995	Snow and Ice	20,382,340
January 3-5, 1997*	Snow and Ice	40,967,085
January 9-10, 1997*	Snow and Ice	54,338,871
February 26-27, 1997*	Snow and Ice	5,466,893
April 5-6, 1997*	Snow and Ice	979,903,066
March 8-9, 1998	Snow and Ice	6,971,880
November 1-2, 2000	Snow	1,524,261
December 15-17, 2000	Snow	49,749,799
January 12, 2005	Snow	178,108,256
November 27-29, 2005	Snow	82,787,917
February 28-March 3, 2007	Snow and Ice	72,707,911
May 1-3, 2008	Snow	7,551,320

Table 4.9. Snowstorm Hazards and Monetary Damage Estimates for 23 Extreme Midwestern Blizzards: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; PERI; FEMA; University of Kansas: GIS and Data Lab Shapefiles; ESRI.
*At least one declaration with damage estimates split between two blizzards.

As shown in Table 4.9, often it was a combination of snow and ice causing the presidential emergency or disaster declarations. After 1999, the “snow and ice” hazard category was discontinued and blizzards and severe ice storms were recognized and delineated as separate entities (PERI 2006), thus explaining the large grouping of snow and ice hazards in the middle 1990s.

Underestimations in loss estimates occurred for the six blizzards in Time Period I. This fact helps explain the "data not available" label in Table 4.9. All these blizzards produced emergency declarations; unfortunately, estimates of loss were not always collected for these types of declarations in the early portion of the study period. In addition, the damage estimate for the March 19-20, 1976, blizzard was not completely correct for this same reason (underestimate of damage). Leaving out the storms where no data was available, the median of damage estimates for the blizzards was $8,424,166 (2008 US Dollars). Based on the type of storm hazards presented in Table 4.9, Table 4.10 provides a summary of state losses resulting from snow and ice associated with extreme Midwestern blizzards.

State	Total Damage Estimate (2008 US Dollars)
Illinois	33,693,103
Indiana	86,925,378
Iowa	98,589,095
Kansas	36,361,822
Michigan	45,805,982
Minnesota	437,496,792
Missouri	0
Nebraska	83,818,187
North Dakota	562,981,325
Ohio	136,396,602
South Dakota	161,978,331
Wisconsin	29,314,836
Total Estimated Damages	1,713,361,453

Table 4.10. Estimated State Damages from Extreme Midwestern Blizzards: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; PERI; FEMA; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

The damage estimates in Table 4.10 range from $0 in Missouri to $562,981,325 in North Dakota (2008 US dollars). The median value in state losses due to extreme Midwestern blizzards was $85,371,782.50 (2008 US dollars). To test for a significant change in level of damages coming from extreme Midwestern blizzards, the values in Table 4.10 were grouped into two categories: Category 1) Lower Damage Estimates; and, 2) Upper Damage Estimates (Table 4.11).

Lower Damage Estimates	Upper Damage Estimates
0	86,925,378
29,314,836	98,589,095
33,693,103	136,396,602
36,361,822	161,978,331
45,805,982	437,496,792
83,818,187	562,981,325

Table 4.11. Grouping of Extreme Blizzard Damage Estimates for Mann-Whitney U Test. Sources: FEMA, PERI.

Using the Mann-Whitney U test based on the data in Table 4.11, the change in damage estimates was found to be statistically significant, $\alpha = 0.05$, $p = 0.004$.

4.7 Blizzard Hazards of Presidential Emergency and Disaster Declarations

4.7.1   Snowstorm Hazards: 6 Blizzards of Time Period I

Six blizzards occurred during Time Period I and produced the pattern of winter weather hazards depicted in Figure 4.8. The map shows the distribution of snow, ice, and snow and ice, the “snow and ice” category being the mixed-precipitation category used by PERI prior to 1999 in describing an assortment of significant winter weather including snowstorms, blizzards, and ice storms (PERI 2006).

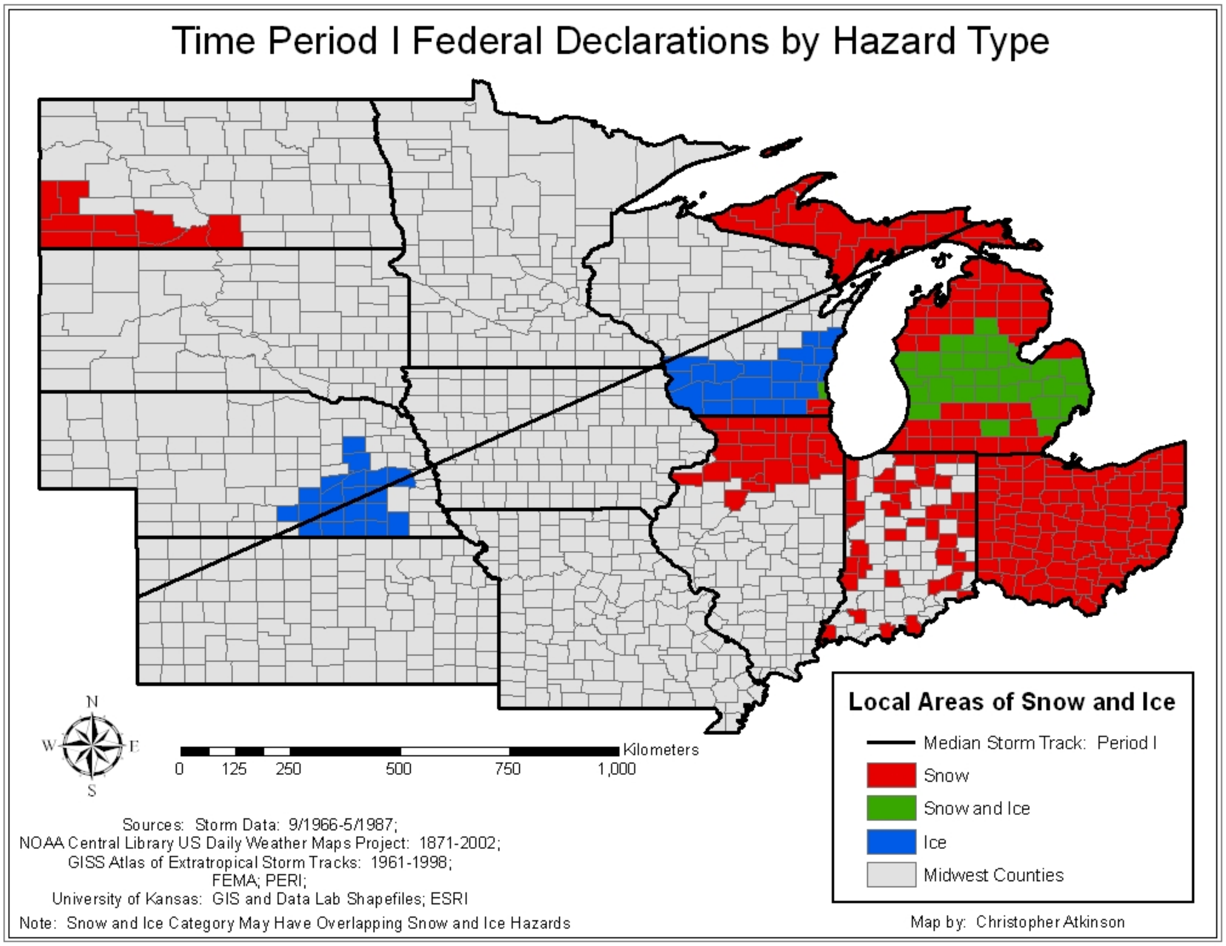


Figure 4.8. The Distribution of Blizzard Precipitation Resulting in Presidential Declarations: September 1, 1966-May 31, 1987. Sources: *Storm Data*: 9/1966-5/1987; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; FEMA; PERI; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Blizzard snowfall during Time Period I created the most federal county disaster and emergency declarations. Hazards related to snowfall predominate the pattern shown in Ohio, Michigan, Indiana, and northern Illinois. A region of mixed snow and ice in the Lower Peninsula of Michigan is an artifact of the method by which these hazards were classified prior to 1999. During that time, severe ice storms were not separated from snowstorms; rather, they were grouped in the same category. So, Figure 4.8 indicates this non-specific hazard classification as indicated in the lower left corner of the map (Figure 4.8): the snow and ice category may have overlapping snow and ice hazards.

The locations of the snow and ice hazards showed some interesting patterns. Contrary to the expected pattern of heavy snowfall to the north and west of a storm's track (Goree and Younkin 1966; Browne and Younkin 1970), most of the county snow-related declarations in Time Period I lie well to the south and east of the median storm track in Illinois, Indiana, Michigan, and Ohio. This pattern suggests one anomalous snowstorm producing a great number of federal declarations: all 83 counties in Michigan and 88 counties in Ohio were declared in need of federal monetary assistance after the January 26, 1978, blizzard. This snowstorm followed a path from north of Lake Superior across the Lower Peninsula of Michigan before veering sharply east across far northern Ohio and the open waters of Lake Erie. In contrast to the location of most of the snow hazards (a small concentration of nine counties in southwestern North Dakota was the exception), ice hazards associated with extreme Midwestern blizzards appeared in their expected locations near or to the south and east of the median storm track.

4.7.2 Snowstorm Hazards: 17 Blizzards of Time Period II

Of 66 total snowstorms, seventeen blizzards occurred during Time Period II and produced the pattern of winter weather hazards depicted in Figure 4.9. The map shows the distribution of snow, ice, and snow and ice hazards. As mentioned in Section 4.7.1, blizzard and ice storm descriptions became independent categories after the 1999 winter season (PERI 2006), and this change in categorization also had bearing on the map visualization of blizzard hazards in Time Period II.

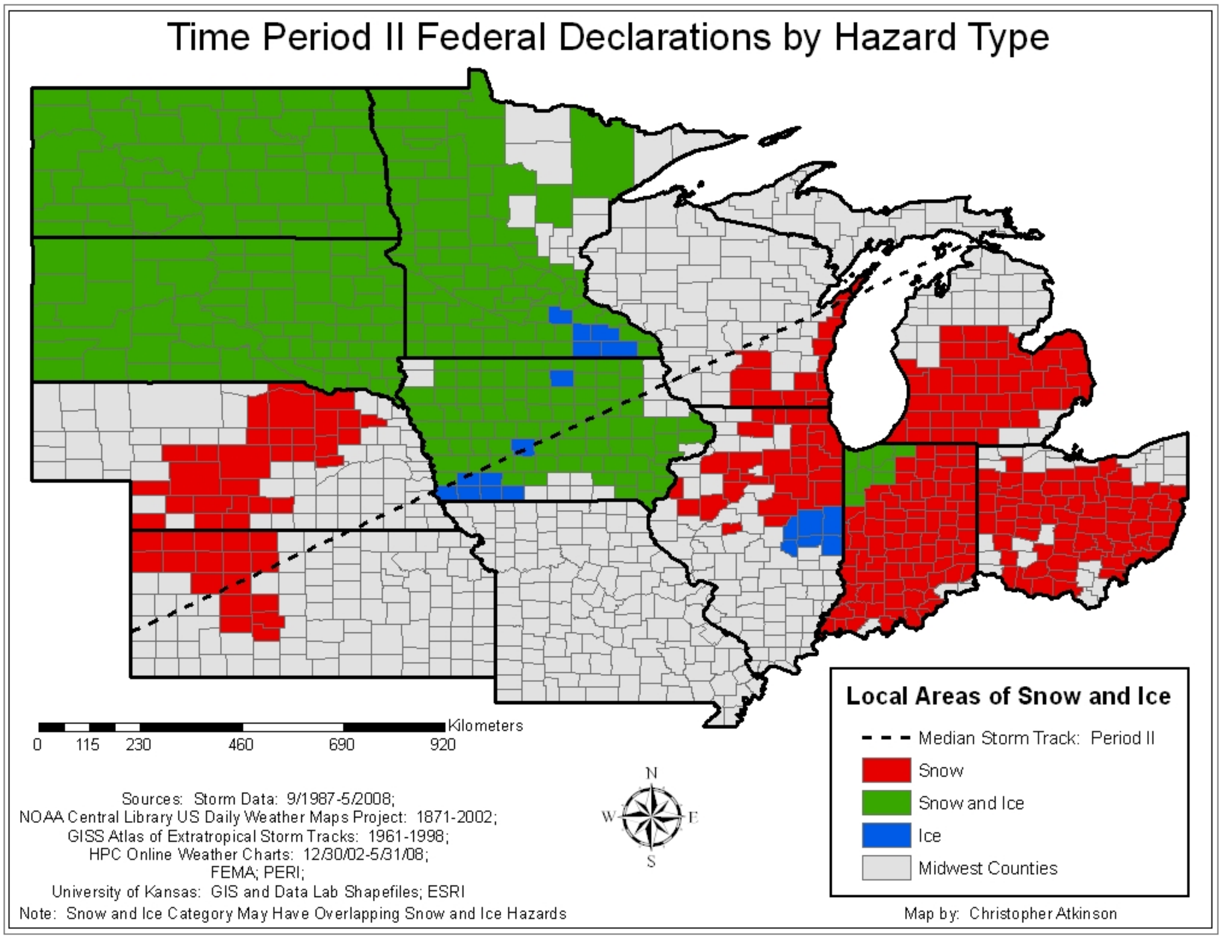
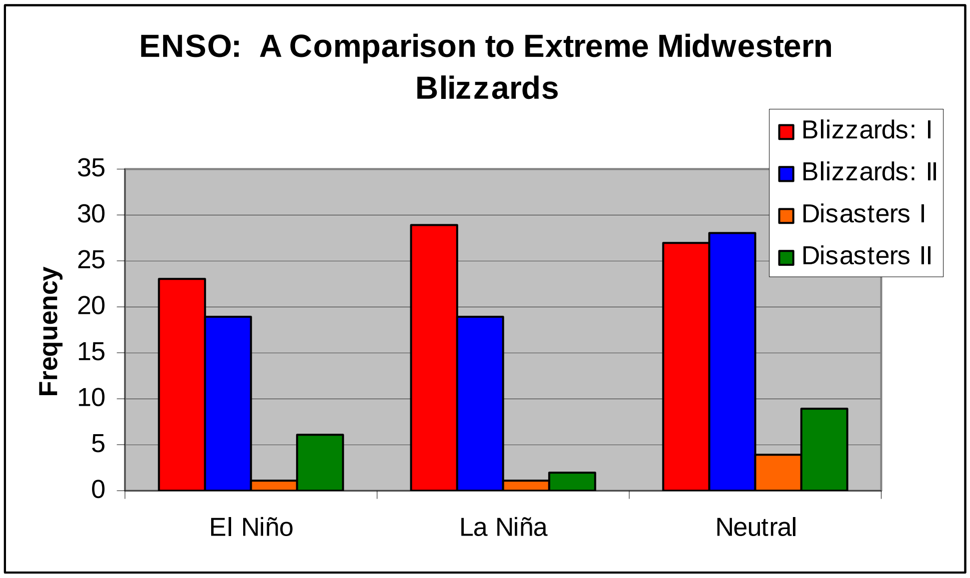


Figure 4.9. The Distribution of Blizzard Precipitation Resulting in Presidential Declarations: September 1, 1987-May 31, 2008. Sources: *Storm Data*: 9/1987-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Blizzard snow and ice hazards in the north and west portions of the study region comprised the most federal county declarations during Time Period II. Hazards related to snowfall predominates the pattern shown in Indiana, Ohio, and the southern region of Michigan's Lower Peninsula. A secondary concentration of snow hazards occurred in central Nebraska and northwestern Kansas. Figure 4.9 also shows a localized region of snow impacts west of Lake Michigan near Chicago and Milwaukee. Ice hazards intersperse the middle portion of the study area with a few counties appearing in Minnesota, Iowa, and Illinois. Two items of note show up on the map: 1) as in Time Period I, the greatest concentration of snow hazards lies to the south and east of the median storm track; and, 2) the snow and ice category in the northern and western regions of the study area hide some of the more regional effects of snow and ice in Iowa, Minnesota, South Dakota, and North Dakota. Sometimes a region in Iowa or another nearby state may have experienced a blizzard with severe icing but without snow; however, as mentioned previously, those patterns do not become apparent until after 1999.

4.8 Extreme Midwestern Blizzards and El Niño/La Niña Indices

Calculations of El Niño, La Niña, and neutral-year indices utilized the Oceanic Niño Index (ONI) from the Climate Prediction Center (CPC 2010j). The ONI indices reflect a 3-month running average. For example, the January index is a composite value reflecting the average of the individual index values for December, January, and February. For this study, a winter season was defined as September through May, so the following indices were averaged to represent the El Niño, La Niña, and neutral years: 1) September-November (SON); 2) December-February (DJF); and, 3) March-May (MAM). To apply an ONI index to the September to May winter-season time sequence, the mean of SON, DJF, and MAM was used to categorize the blizzard storm tracks. The mean winter ONI indices indicated whether an El Niño, La Niña or neutral pattern was in effect. El Niño (ONI $\geq +0.5$), La Niña (ONI ≤ -0.5) and neutral-year (ONI -0.49 to +0.49) index definitions were used to categorize the 145 blizzards occurring between September 1, 1966 and May 31, 2008. To get a sense of the relationship between extreme Midwestern blizzards and the El Niño/La Niña phenomenon, all 145 storm tracks were grouped by time period and the ONI indices. From these indices, it was possible to categorize all 79 snowstorms in Time Period I and all 66 snowstorms in Time Period II by El Niño, La Niña, and neutral phases as specified by the ONI. Graph 4.4 reflects the visual representation of this classification.



Graph 4.4. ENSO Compared to Extreme Midwestern Blizzards: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; CPC: Cold and Warm Seasons by Episode; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Graph 4.4 depicts the frequency of El Niño, La Niña, and neutral-year blizzard storm tracks for Time Periods I and II and any subsequent federal declarations that occurred as a result of the blizzards. There is no clear trend in the graph. The results failed to indicate any greater number of extreme Midwestern blizzards during El Niño, La Niña, or neutral-year patterns. Using the Mann-Whitney U test, the statistical significance regarding the change in frequency and federal declarations can be tested.

Variable to Test	El Niño	La Niña	Neutral
Frequency	0.158	1.000	0.892
Declarations	0.086	0.332	0.189

Table 4.12. P Values Regarding the Statistical Comparison of Blizzard Frequency per Time Period and ENSO Phase: September 1, 1966 to May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; CPC: Cold and Warm Seasons by Episode; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Table 4.12 shows that none of the changes in blizzard frequency or federal declarations classified as El Niño, La Niña, or neutral-phase extreme Midwestern blizzards were statistically significant at $\alpha = 0.05$ (refer to Graph 4.4). Nonetheless, Graph 4.4 indicates: 1) the largest drop in storm frequency occurring between Time Period I and II during the La Niña-phase; and, 2) the number of federal declarations in Graph 4.4 is highest during Time Period II for all three phases. These changes in frequency and number of declarations closely follow previous results.

Figure 4.10 shows a comparison of three sets of blizzards storm tracks correlated to the ONI indices representing the El Niño, La Niña, and neutral-year phases.

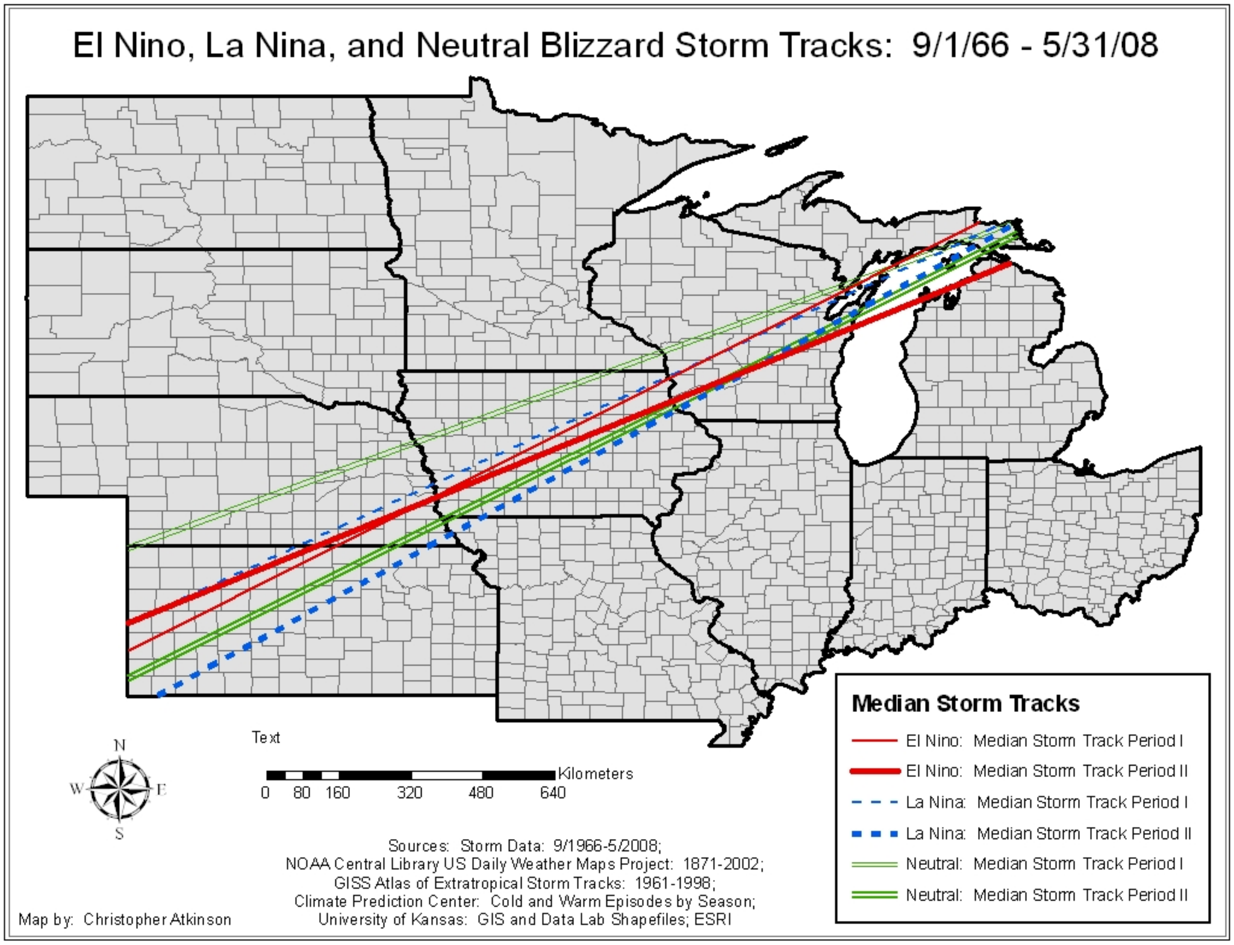


Figure 4.10. El Niño, La Niña, and Neutral Median Storm Tracks for Time Periods I and II: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; CPC: Cold and Warm Seasons by Episode; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Figure 4.10 shows a tight clustering of various ENSO-phase storm tracks. Every one of the storm tracks, regardless of phase, follows the southwest to northeast trajectory typical of both Time Periods I and II. Table 4.13 shows the azimuth directions for all six of the storm tracks.

Storm Track Azimuth	El Niño	La Niña	Neutral
Azimuth: Period I	243.3	245.5	249.8
Azimuth: Period II	247.9	241.2	243.5

Table 4.13. El Niño, La Niño, and Neutral Phase Storm Track Trajectories: September 1, 1966-May 31, 2008. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; CPC: Cold and Warm Seasons by Episode; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Blizzard storm track azimuths categorized according to El Niño, La Niña, and neutral-year ONI phases show few differences when compared to previous median storm tracks in Figures 4.2 and 4.3. All three sets of latitude and longitude coordinates cluster tightly around the common southwest to northeast median blizzard storm track path favored by blizzards in Time Periods I and II.

Variable to Test	El Niño	La Niña	Neutral
Latitude	0.928	0.514	0.138

Table 4.14. P Values for El Niño, La Niña, and Neutral-Phase Blizzard Storm Track Shifts. Sources: *Storm Data*: 9/1966-5/2008; NOAA Central Library US Daily Weather Maps Project: 1871-2002; GISS Atlas of Extratropical Storm Tracks: 1961-1998; HPC Online Weather Charts: 12/30/02-5/31/08; FEMA; PERI; CPC: Cold and Warm Seasons by Episode; University of Kansas: GIS and Data Lab Shapefiles; ESRI.

Table 4.14 shows the lack of any statistically significant shifts in latitude position for extreme Midwestern blizzards in the context of El Niño, La Niña, and neutral-phase storm tracks, $\alpha = 0.05$. The similarity trajectories for the El Niño, La Niña, and neutral-phase storm tracks was to be expected since a majority of blizzards in Time Periods I and II followed this same route. When compared to El Niño, La Niña, and neutral-year indices, extreme Midwestern blizzards do not show a convincing pattern, and it would be very difficult to state with any amount of conviction that extreme Midwestern blizzards develop more frequently during a certain phase of the ENSO cycle.

Chapter 5: Discussion

This study focused on exploring extreme Midwestern blizzards to reveal how these storms may be changing in light of rising global/United States temperatures. With concerns about the impacts these storms could bring to the Midwest within the context of climate change, it is important to explain the findings of this research.

5.1 Blizzard Frequency in the Midwest

The change in frequency of extreme Midwestern blizzards was found to be not statistically significant. Based on a comparison of the means of the two 21-year time periods with 79 storms in Time Period I and 66 storms in Time Period II, the total decrease was 13 snowstorms, or 16.5 percent. This result could be considered a surprising result considering 29 blizzards (36.7 percent) occurred in four winter seasons during Time Period I: 1) 1966-67: 5 snowstorms; 2) 1968-69: 7 snowstorms; 3) 1970-71: 10 snowstorms; and, 4) 1982-83: 7 snowstorms. The 1970-71 season also was the highest storm total in the 42-year study with 6.9 percent of all blizzards (145 total storms) included in the study. Interestingly, even with an average of 7.3 storms for those four winters (1966-67, 1968-69, 1970-71, and 1982-83), the difference in means was not sufficient to produce a statistically significant decrease in blizzard frequency.

The change in blizzard frequency may be explained by comparing the December through May and September through November snowstorm frequencies for Time Periods I and II. A total of 68 storms occurred between December and May in Time Period I compared to 51 storms in Time Period II for a decrease of 25 percent in the number of snowstorms. The frequency of Time Period II October and November storms increased compared to the Time Period I storms. In October, Time Period II saw three storms compared to one storm in Time Period I. Twelve

November snowstorms were seen in Time Period II versus ten in Time Period I. Since the decrease in blizzards (25 percent or 17 storms) between December and May was greater than the 16.5 percent (13 storms) for all nine months (79 to 66 storms), it seems the reason for the lack of a statistically significant change in the means regarding the number of snowstorms could be attributed to the offsetting effects of the October and November snow events, and the high inter-annual variability associated with these extreme storms.

5.2 Blizzard Intensity in the Midwest

Like frequency, the change in blizzard intensity was also shown to be not statistically significant for this study. After completing the two-tailed t test, p = 0.084, the null hypothesis was not rejected indicating no statistically significant difference in the means regarding blizzard intensity. To know why this occurred, it is necessary to examine the specific mean storm intensities for the two time periods.

The p value of 0.084 was close to significant, and that result is supported by the mean central pressure comparisons. In Time Period I, the average intensity was 986.0 mb (79 storms). Comparing the storm intensity from Time Period I with Time Period II, the mean minimum central pressure for the snowstorms during Time Period II actually increased to 987.6 mb (66 storms). The reason for this decrease in snowstorm intensity is directly linked to one specific storm that occurred during Time Period I.

Toward the end of January, 1978, an anomalous snowstorm severely affected all of Michigan and Ohio. Traveling in a somewhat unconventional path from the Upper Lakes and across a portion of the Lower Peninsula of Michigan, the storm then veered sharply to the east and touched a portion of northern Ohio before moving east across Lake Erie. While the Upper Lakes may have contributed to its strengthening (Angel and Isard 1997), it was this storm with its minimum central pressure of 964.0 mb that most likely prevented Time Period II from having a lower average minimum central pressure (it should be noted that even if the mean minimum central pressure was lower during Time Period II, there is no guarantee that a statistically significant result would ensue). As it turned out, this storm, the strongest of all 145 blizzards, was enough to produce a differential increase of 1.6 mb in mean minimum central storm pressure even though there were fewer storms in Time Period II (meaning that any similarly low values were not great enough to produce an off-setting effect even though their effect would have been greater since there were fewer blizzards in the second time period).

5.3 Blizzard Statistics in the Midwest

The aim of the logistic regression analysis for this study was to accurately predict which storm characteristics (described statistically according to seven independent variables) would correctly predict the occurrence of a federal emergency or disaster declaration, the dependent variable, due to extreme Midwestern blizzards. Unfortunately, this process did not work well.

After substituting AZIMUTH for the ICE THRESHOLD variable, two separate logistic regression processes were carried out on the data. In the first process, the model ran two iterations. After the second iteration, two independent variables, MINIMUM CENTRAL PRESSURE and ABSOLUTE MAXIMUM TEMPERATURE IN THE WARM BUFFER had entered the model with the predictive capacity of the model only increasing 1.3 percent to 93.7 percent with $R^2 = 0.169$. As mentioned previously, the second logistic regression model failed to even run one iteration because the significance values to enter were above the $\alpha = 0.10$ threshold.

Seven independent variables, SNOWFALL_COLD, SNOWFALL_WARM, MINIMUM TEMPERATURE_COLD, MAXIMUM TEMPERATURE_WARM, MAXIMUM STORM DROP TEMPERATURE, AZIMUTH, and MINIMUM CENTRAL PRESSURE were used in the two logistic regression models. None of these independent variables did a good job at capturing when a federal declaration would most likely occur. Three reasons are considered to help explain the poor model output.

One reason for this may be linked to a poor choice of independent variables. By somehow statistically capturing (via an alternate independent variable) the moisture available to these blizzards, the predictive capacity of the model may have improved. A second consideration that was not included in this study would be trying to delineate and represent lake effect snow within these blizzards, since heavier snows intuitively are associated with greater chances for hazardous impacts and the potential for more FEDD. Finally, it appears that FEDD are not related to storm strength or intensity, but may rather be correlated to other factors. For example, the FEDD might have been linked to the storm events, but indirectly as a result of flooding or other factors that are not represented in the independent variables used in this study.

5.4 Changes in Blizzard Storm Tracks and Storm Track Variation

This study also indicated an insignificant southward shift in median storm tracks from Time Period I to Time Period II along with a reduction in the variability of storm tracks north of the median track based on the latitudinal start and end points of extreme Midwestern blizzards. As before, this result seems to follow the common theme of this research: expected outcomes as indicated by the IPCC (2007) really were not statistically supported by this study. In this case, a poleward shift in blizzard tracks, predicted as an effect of global warming (IPCC 2007), was not evident in the data. If anything, the tracks moved southward. Even though this study did not support the IPCC’s assertion of a poleward shift in snow events in the context of climate change, it does not necessarily mean that extreme Midwestern blizzards are not shifting northward and lessening in their variability; rather, it indicates the need for more research to ascertain what factors are most meaningful when trying to learn more about how these types of snowstorms react in changing environmental scenarios. As an example, a future study using the same template for research with a longer time period or a different pressure threshold criteria (something other than 992 mb) for storm inclusion may have indicated different results which could have led to statistically significant outcomes concerning the latitudinal shifts in these snowstorms. It is also possible that the extreme winter storm events, as represented by blizzards, may show a systematic change in location because their underlying causes (a particular jet stream behavior) are not drastically affected by climate change.

5.5 Changes in Federal Declaration Areas

In comparing Time Period I to Time Period II, the challenge was to explain the distributions of federal declarations in the 12-state study region. Specifically, how does one go about explaining the distribution of snow hazards that is contrary to heavy-snowfall climatology (Goree and Younkin 1966; Browne and Younkin 1970).

During Time Period I, one storm accounted for all the counties in Michigan and Ohio being named federal declaration areas: the January 26, 1978 blizzard. This singular blizzard tracked in a similar fashion to an Alberta Clipper; however, it skimmed the Upper Lakes before tracking south across the Lower Peninsula of Michigan before veering sharply to the east across northern Ohio and out across Lake Erie. Although it was late in the season for open water on the Great Lakes, any ice-free lake waters probably contributed to storm strengthening as the storm tracked south-southeast across Michigan and Ohio (Angel and Isard 1997). In contrast, sometimes a number of storms within the same winter season create favorable conditions for emergencies and disasters due to snowfall as associated with blizzards.

Nine blizzards occurred in Grand Forks, North Dakota, during the 1996-1997 winter season. The last blizzard, Blizzard Hannah, was the final snowstorm in an above-average season for blizzards. Grand Forks and environs received 271.0 cm (106.7 in) of snow (Enz and Brockberg 1997) which was 180.3 cm (71.0 in) above average based on the 1961-1990 climatological data (NCDC 2010k). The great amount of snowfall and wind during the 1996-1997 season culminated by Blizzard Hannah epitomized the level of impact possible during a high-frequency blizzard season. The end result of these blizzards was all 53 counties in North Dakota and 66 counties in South Dakota being declared federal disasters in the spring of 1997 (PERI 2006; FEMA 2010), mainly due to rapid snowmelt and subsequent flooding along the Red River of the North.

5.6 Hazard Impacts on Population

One finding of this research was the slight shifting of the counties experiencing storm track intersections, as explained in the methodology and displayed in the results. The intersections (areas impacted by extreme Midwestern blizzards) moved to the south and west which is contrary to some of the published scientific predictions for United States wintertime extratropical cyclones (IPCC 2007). The reason for this unexpected result is not clearly understood from this research; however, a more extensive study with an expanded timeframe could have produced different results regarding the temporal and spatial characteristics of blizzards in the Midwest. Nonetheless, the shift that was found in this study could have potential future impacts on the current and future populations in the region.

According to 2009 estimates by the United States Census Bureau, the population of the study area was 66,836,911 residents. As indicated in Table 5.1, the ten largest cities and corresponding metropolitan areas make up a large percentage of the population that lie near or in the direction of blizzard shifts as presented in this research. Tables 5.1 and 5.2 highlight the growth in states and metropolitan areas located in the Midwest.

State	2009 Est. Population	Metropolitan Areas	2009 Est. Population
Illinois	12,910,409	Twin Cities, MN	3,269,814
Indiana	6,423,113	Omaha, NE/Council Bluffs, IA	849,517
Iowa	3,007,856	Kansas City, MO/KS	2,067,585
Kansas	2,818,747	St. Louis, MO/IL	2,828,990
Michigan	9,969,727	Chicago, IL/IN/WI	9,580,567
Minnesota	5,266,214	Milwaukee, WI	1,559,667
Missouri	5,987,580	Indianapolis, IN	1,743,658
Nebraska	1,796,619	Columbus, OH	1,801,848
North Dakota	646,844	Cleveland, OH	2,091,286
Ohio	11,542,645	Detroit, MI	4,403,437
South Dakota	812,383		
Wisconsin	5,654,774		
Total	66,836,911		30,196,369

Table 5.1. Midwestern State and Metropolitan Populations: 2009 Estimates. Source: Adapted from the United States Census Bureau.

Table 5.1 shows the total number of Midwestern residents living in the twelve states in the study region and the populations of the ten metropolitan areas associated with the ten largest cities. In addition, the change in population of these regions also should be considered in evaluating the future impacts from extreme Midwestern blizzards.

State	Est. 2009 Population	1970 Population	Raw Change	Pct.Change
Illinois	12,910,409	10,977,908	1,932,501	17.6
Indiana	6,423,113	5,143,422	1,279,691	24.9
Iowa	3,007,856	2,789,893	217,963	7.8
Kansas	2,818,747	2,222,173	596,574	26.8
Michigan	9,969,727	8,778,187	1,191,540	13.6
Minnesota	5,266,214	3,767,975	1,498,239	39.8
Missouri	5,987,580	4,626,842	1,360,738	29.4
Nebraska	1,796,619	1,468,101	328,518	22.4
North Dakota	646,844	611,648	35,196	5.8
Ohio	11,542,645	10,542,030	1,000,615	9.5
South Dakota	812,383	657,098	155,285	23.6
Wisconsin	5,654,774	4,366,766	1,288,008	29.5
Total	66,836,911	55,952,043	10,884,868	19.5

Table 5.2. Change in State Populations: 1970-2009. Source: US Census Bureau.

Table 5.2 shows that all states in the Midwestern study region have increased in population between 1970 and 2009 (19.5 percent across all 12 states) with percentage increases in population during this 40-year period ranging from 5.8 percent in North Dakota to 39.8 percent in Minnesota (U.S. Census Bureau 2010a; U.S. Census Bureau 2010p). This indicates that as extreme Midwestern blizzards continue in the future, the impact to states' citizens will continue too. Of course, how different areas react to the future impacts is partly dependent on the population density along with the built-up infrastructure housed mainly in larger cities and metropolitan areas.

City	Est. 2006 Population	1970 Population	Pct. Change
Minneapolis	372,833	434,400	-14.2
Omaha	419,545	347,328	20.8
Kansas City	447,306	507,087	-11.8
St. Louis	347,181	622,236	-44.2
Chicago	2,833,321	3,366,957	-15.8
Milwaukee	573,358	717,099	-20.0
Indianapolis	785,597	744,624	5.5
Columbus	733,203	539,677	35.9
Cleveland	444,313	750,903	-40.8
Detroit	871,121	1,511,482	-42.4
Total	7,827,778	9,541,793	-18.0

Table 5.3. Ten Largest Midwestern Cities: Change in Population, 1970-2006. Source: US Census Bureau.

Table 5.3 indicates that the ten largest cities have generally decreased in population between 1970 and 2006 with the exceptions of Omaha, Nebraska, Indianapolis, Indiana, and Columbus, Ohio. In addition, these trends show that traditional city cores have decreased in population, while suburban areas have grown, and this trend could lead to potential new vulnerabilities from blizzards. Currently, approximately 45 percent of the residents in the Midwest live in the ten largest cities according to 2009 population estimates (US Census Bureau 2010d; Census Bureau 2010e; Census Bureau 2010f; Census Bureau 2010g; Census Bureau 2010i; Census Bureau 2010k; Census Bureau 2010l; Census Bureau 2010m; Census Bureau 2010n; Census Bureau 2010o; Census Bureau 2010p). The high prevalence of residents living in cities indicates that urban impacts due to Midwestern blizzards will continue in the future. In addition, the proximity of certain cities to the Great Lakes could have detrimental effects on blizzard impacts in the future.

As extreme Midwestern blizzards shift in the future, the largest cities along the Great Lakes, like Cleveland, Ohio, could experience more lake effect snows as the waters of the Lakes warm in the face of climate change. This warming could lead to delayed icing of the Lakes and potentially could contribute to enhanced snowfall totals for the cities on the downwind shores of the Great Lakes.

5.7 Changes in Blizzard Declarations and Damages

The significant increase in disaster and emergency declarations in Time Period II can be explained in many ways. There are five possible reasons to explain the statistically significant rise in Federal Declarations in Time Period II (973 vs. 378): 1) sheer number of storms; 2) May snowstorms; 3) increase in infrastructure/population; 4) a blizzard's forward speed, precipitation and wind characteristics; and, 5) a region's experience with winter storms.

As mentioned in Section 5.5, the sheer number of storms in a given season may produce effects exceeding normal climatological conditions and extending hazards beyond the capacity of residents' ability to cope. The North Dakota winter of 1996-97 produced the greatest seasonal snowfalls on record in Fargo, 297.2 cm (117.0 in), Grand Forks, 271.0 cm (106.7 in), and Bismarck, 258.1 cm (101.6 in) (Enz and Brockberg 1997). The amount of snowfall in Grand Forks was four standard deviations above normal (Todhunter 2001). For Grand Forks, eastern North Dakota, and northwestern Minnesota, the timing of the snowfall was a major issue. Late-season snowfalls in North Dakota are not unusual; however, when additional storms came after a winter that had seen several blizzards already with frozen soils that allowed for no moisture infiltration during the winter (Enz and Brockberg 1997; Todhunter 2001), it created an environment characterized by extensive snowpack with warming temperatures and the threat for severe spring flooding. In addition to having numerous blizzards during the winter season, sometimes heavy, late-season snowfalls set records during blizzard events because of the high moisture content in the relatively warm atmosphere.

In May, 2008, the Black Hills region of South Dakota experienced major, record-setting snowfalls. Belle Fourche, 30.5 cm (12.0 in), Martin, 25.4 cm (10.0 in), Camp Crook, 57.7 cm (22.7 in), Long Valley, 38.1 cm (15.0 in), and Bison, 25.4 cm (10.0 in) were all two-day snowfall records in a storm lasting from May 1-2, 2008 (PERI 2006; NCDC 2010c; NCDC 2010g; NCDC 2010e; NCDC 2010f; NCDC 2010d). This amount of snowfall was quite unusual because all these stations average one inch or less of snowfall during May (NCDC 2010h; NCDC 2010m; NCDC 2010j; NCDC 2010l; NCDC 2010i). In addition to enormous amounts of spring snowfall totals, sometimes a blizzard's forward speed can also affect the spatial distribution of declarations.

A blizzards forward speed, precipitation and wind characteristics can have an effect on whether emergency and disaster declarations are experienced in a region. Most of the 145 blizzards in this study were either Kansas Lows or Alberta Clippers. Generally, Alberta Clippers move more slowly and have less moisture than Kansas Lows (Moran and Morgan 1997; Lutgens and Tarbuck 2007). Regardless of the storm type, if a storm moves slowly or stalls in a region it most likely will produce greater impacts. In addition to forward speed, the type of precipitation can have a major impact on whether declarations occur. For example, if Bemidji, Minnesota, located about two hours south of Canada, were to receive one inch of freezing rain, this would have a much greater impact on the local residents than 30.5 cm (12 in) of snow associated with a blizzard because the local population does not expect heavy icing during the winter season. Finally, the combination of a stalled snowstorm with heavy snowfall and high winds would produce the greatest impact in any region within the study area. Although not included in the study, the Christmas 2009 blizzard over the Upper Midwest would be a good example of a storm that stalled in the Upper Midwest bringing blizzard conditions from the Northern Plains to the western reaches of Lake Superior and southward to the Missouri/Kansas border (HPC 2009). These types of storms are very rare and only make up a small percentage of the storms included in this study.

As alluded to in the previous paragraph, different regions within the study area will respond in various ways to similar storms. For example, six inches of snowfall in southern Missouri with high winds would close schools and create major transportation impacts. A similar magnitude/intensity snowstorm in northern Wisconsin might lead to a late school start and fresh powder for snowmobilers with not nearly the impact to highways and transportation infrastructure/resources.

Changes in the temporal and spatial characteristics of FEDD guidelines also partially accounted for how these disasters were defined by the national government and deemed appropriate for inclusion in state-level storm reports. Nationally, the procedure by which ice storms and snowstorms/blizzards was defined changed in the late 1990s (PERI 2006), and this could have influenced the number of federal declarations. In 1999, blizzard icing and heavy snowfall were included all together in one category. As shown on the maps included in this research, the snow and ice category (refer to Figures 4.8 and 4.9) suggests that potentially some of the unique patterns of snow and ice were lost when both types of precipitation hazards were grouped together. In other words, more counties with ice might have been separated from snow, and this might have led to more (or less) counties being declared federal emergency and disaster areas. Nationally, the way in which these extreme blizzards were defined could have led to changes in the areas that were deemed in need of monetary assistance. The method by which individual states reported blizzards also had an influence on which counties were federally declared in need of assistance.

Storm Data revealed some interesting patterns concerning how individual states reported snowstorms. Each state sends in reports individually, and there is no standard by what needs to be included in the reports. Specifically, Figure 4.7 (in Section 4.6), showing the spatial distribution of federal declarations during the first time period indicates declarations in Michigan and Minnesota but not in Wisconsin. This artifact is a result of how the individual states determine the need of local residents. It also might suggest the density of population may have an influence on FEDD. Northern Wisconsin contains a low population density such as Iron

County with 9.1 persons per square mile versus Gogebic County right adjacent in Michigan with 15.8 persons per square mile (U.S. Census Bureau 2010j; U.S. Census Bureau 2010h). The difference in density is not great between the two counties, although Ironwood, a larger city is located at the western end of Gogebic County. Low population density equates to less potential impact, and this is portrayed in the manner in which Wisconsin has decided in the past to report to *Storm Data*, if one assumes that a listing in *Storm Data* is the first step toward garnering a federal declaration and the subsequent monies that come along with that. It is interesting to note that storm tracks had nothing to do with the lack of Wisconsin counties showing up on the maps, since a majority of the tracks led to northeastern Wisconsin and Michigan. Michigan saw a number of emergency and disaster declarations, while Wisconsin was lacking in this regard. Even so, the difference in declarations is not based on residents' experience with winter storms, since both parties would be seasoned veterans of winter storms and related weather conditions. This further suggests that the *Storm Data* reports are left to the discretion of local state authorities. The way in which these extreme Midwestern blizzards have been defined and grouped by the federal government and reported by individual states is closely related to the estimates of damages associated with these storms.

There was a wide range in the damage estimates due to extreme Midwestern blizzards (Table 4.9). The range in damage estimates is directly related to how the particular precipitation hazards were defined (snow versus ice) and the effect of related hazards that were grouped in with snow and/or ice inflated the estimates beyond those losses that could have been directly attributable to snow and ice. Rather, a portion of flooding losses was seen to be included in the damage estimates, especially those resulting from the Red River Valley floods of 1997.

5.8 Blizzard Climatology and Declarations

In several cases, some of the precipitation hazards associated with extreme Midwestern blizzards were not clearly delineated. Specifically, it was difficult to show areas that received severe icing associated with snowstorms. For example, due to the Halloween blizzard of 1991, 44 counties in Iowa and 12 counties in Minnesota received federal funds due to downed power lines and other major impacts associated with severe icing. Blizzards occurring in the springtime could be influenced by a warming atmospheric column, and this could lead to icing conditions north of storm tracks that might not see similar conditions during the middle winter months of December, January and February.

Based on the results of this scientific study and examples such as the North Dakota FEDD patterns, it seems that blizzard storm tracks do not align with FEDD, suggesting a weak correlation between storm climatology and FEDD. In fact, it appears that specific (and usually unexpected) impacts of individual storms lead to FEDD most of the time. Since FEDD are usually linked to very few individual storms, there is no link to FEDD based on climatology.

Schmidtlein, et al. (2008) also discovered that federal declarations do not always get directed to counties most in need of funds. Schmidtlein, et al. (2008) suggested that counties declared disaster areas in the past generally have a better chance of seeing future declarations. This fact suggests that emergency and disaster declarations along with the monies that come with it are more politically driven than based on any sort of climatology associated with these storm systems. PERI (2006) lists the number of federal declarations issued by each President. Dr. Lisa Keys-Mathews of the University of North Alabama, while attending a presentation by the author on April 22, 2010, went further to suggest that the party affiliation of the President and the declarations given may be linked to the political party of state governors and influenced by the most prominent leaders of Congress. If true, political decisions of this nature have nothing to do with winter storm climatology and the hazards related to blizzard snowfall and severe icing events.

5.9 Blizzards and El Niño, La Niña, and Neutral Phase Patterns

There was no distinct pattern found between extreme Midwestern blizzards and the El Niño/ La Niña patterns. Each pattern has certain characteristics and variations with a different temporal signature which make it difficult to suggest any long-term positive connection to Midwestern blizzards with any level of confidence or accuracy.

Different years between 1966 and 2008 can be compared to suggest that large Midwestern blizzards occur in El Niño, La Niña, and neutral phases. The storm that sank the *Edmund Fitzgerald* on November 10, 1975, and its anniversary storm on November 10, 1998, both came during La Niña phases. Another big winter storm in the Midwest was the March 2-5, 1985, storm that hit the Upper Midwest with over a foot of snow and high winds, enough to create major drifts in west-central Minnesota. Unfortunately, the correlation between blizzards and ENSO phases is not direct since some major blizzards also occur during La Niña regimes. The Halloween Blizzard of October 31-November 2, 1991, occurred during a moderately strong El Niño (CPC 2010j). Other Midwestern blizzards come during neutral phase scenarios. The January 22-23, 1982 blizzard prevented Carl Ford from delivering his newspapers on time, forcing him to sacrifice a part of his birthday to deliver the papers the following Monday, January 25, 1982 (Personal Communication 4-13-10). At other times, blizzards over several winter seasons were characterized by all three phases, as indicated during the late 1970s (CPC 2010j).

Chapter 6: Conclusions

6.1 Summary of Study

This study investigated extreme Midwestern blizzards occurring in a 12-state region defined as Kansas, Nebraska, South Dakota, North Dakota, Minnesota, Iowa, Missouri, Wisconsin, Michigan, Illinois, Indiana, and Ohio. Using resources such as *Storm Data*, the GISS Atlas of Extratropical Storm Tracks 1961-1998, the HPC Online Weather Charts, and the NOAA Central Library US Daily Weather Maps Series, 1871-2002, a total of 145 blizzards were identified and mapped in ArcGIS 9.3. Comparisons of these numerous blizzards attempted to ascertain three items: 1) to what degree has the temporal and spatial characteristics of these blizzards changed over time in the context of climate change; 2) what meteorological characteristics best describe these blizzards, and can these variables predict the occurrence of a presidential disaster or emergency declarations; and, 3) what is the spatial pattern of federal declarations and related precipitation hazards (snow and ice) across the Midwest, and how well do the blizzard hazards (the precipitation hazards that prompted the declaration) fit within the concept of cold and warm regions of snowstorms.

6.1.1 Frequency, Intensity, and Mapping of Extreme Midwestern Blizzards

For this study, the winter season spanned nine months from September through May. Temporal blizzard comparisons encompassed a 42-year study period divided into two 21-year segments. Time Period I extended from September 1, 1966-May 31, 1987, and Time Period II examined blizzards from September 1, 1987-May 31, 2008. The total and mean number of blizzards decreased over time. Time Period I saw 79 blizzards (Mean: 3.8) compared to 66 blizzards during Time Period II (Mean: 3.1), a statistically insignificant ($p = 0.302$) decrease at α

= 0.05. Similarly, the intensity of these storms did not deepen significantly over time, $p = 0.084$, $\alpha = 0.05$.

Mapping of 145 storm tracks within ArcGIS indicated southwest to northeast trajectories for most of the blizzards. Azimuths indicated the storm track trajectories, and these azimuths were calculated in ArcGIS based on latitude and longitude start and end points for each of the 145 blizzards. The median storm track trajectory for Time Period I was 246.0° and Time Period II was 245.0°. In addition, the variation in storm tracks both north and south of the median track showed a greater variance about the median track during Time Period I. Most storm track termini occurred across the Great Lakes. The overall change in median storm tracks was slightly southward from Time Period I to Time Period II, although this change proved to be statistically insignificant, $p = 0.508$, $\alpha = 0.05$, and the directional change was opposite to the asserted hypothesis. Some blizzards followed the typical track for Alberta Clippers, tracking southeast toward the northern portion of the study region and sometimes across the Great Lakes. A few blizzards tracked northeast in the southeastern portion of the study region: the best example being the January 26, 1978, blizzard that produced very winter-like conditions for all of Ohio and Michigan. Few blizzards tracked south-to-north, north-to-south, or west to east. One exception was the Halloween Blizzard of October 31-November 2, 1991.

6.1.2 Statistical Analysis of Extreme Midwestern Blizzards

Logistic regression analyses attempted to ascertain when extreme Midwestern blizzards resulted in federal emergency or disaster declarations. During the 42-year study, twenty-three blizzards (15.8 percent) prompted federal county declarations with 6 in Time Period I and 17 in Time Period II. Logistic regression utilized seven independent variables designed to describe the meteorological characteristics of the snowstorms that would capture the conditions necessary to model when declarations did occur (the dependent variable). Two models using the Forward LR approach for variable entry (Enter: $\alpha = 0.10$; Remove: $\alpha = 0.15$) were developed in SPSS, and neither one adequately predicted the occurrence of presidential declarations. The first model showed the most promise with 16.9 percent of the variation in the dependent variable explained by the minimum central pressure and absolute maximum temperature in the warm buffer in two model steps. The poor performance of the model indicated two possibilities: 1) the independent variables used for this analysis did not adequately capture the meteorological variables associated with extreme Midwestern blizzards; and/or, 2) local and regional effects (ie the Great Lakes) affected the magnitude of blizzards and the potential for federal declarations more than the meteorological characteristics of these storms. Results of this study suggest that FEDD seem to be, at least partially, driven more by political decisions at the state and federal governmental levels than by blizzard climatology.

6.1.3 Hazards Associated with Extreme Midwestern Blizzards

Extreme Midwestern blizzards in this study produced three types of hazardous precipitation: 1) snow; 2) ice; and, 3) mixed snow and ice. As mentioned in section 6.1.2, These three forms of frozen precipitation helped prompt twenty-three blizzards (6 during Period I and 17 during Period II) to be declared serious enough for residents of the Midwest to garner monies from the federal government. Mapping the hazards associated with these 23 blizzards revealed that blizzard hazards associated with federally-declared snowstorms do not always fit the model of snow in the cold air and ice in the warmer region of the blizzard. Equally unusual was mixed snow and ice hazards north of the median storm track during Time Period II.

During the first time period, snow hazards south and east of the median storm track were unusual. Places within Ohio not affected by lake-effect snow may not have been as accustomed to severe blizzards as much as residents living in the northern regions of the study area. Weather conditions are partly weather perception; in other words, if weather conditions stray too much beyond what is defined locally as “expected wintertime weather”, then that situation becomes hazardous and is viewed as dangerous. So, hazardous weather is a product of geographic location and associated with a person’s experience and ability to cope with severe winter storms and weather conditions. What may be a major storm in southern Indiana or Ohio may not be perceived as such in northern Minnesota or Wisconsin. Winter-weather hazards are a product of the area being affected.

Equally unusual was mixed snow and ice hazards north of the median storm track during Time Period II. Regions of northwestern Minnesota and eastern North Dakota experienced ice during the spring of 1997. This weather scenario occurred in early April, so the atmosphere may have warmed enough aloft during the springtime to produce these icing conditions. Icing also is a product of where a storm tracks and whether there is warm air above a cold surface layer. More importantly and to clarify, PERI grouped all storm hazards occurring prior to 1999 into the “snow and ice” hazard label. After 1999, severe ice storms had their own category, so this shortcoming was removed. Nonetheless, the method by which the storm were classified hid some ice hazards that would have been more noticeable: for example, during the Halloween Blizzard of 1991, there were 44 counties in Iowa and 12 in Minnesota declared disaster areas due to severe icing (PERI 2006).

6.1.4 Extreme Midwestern Blizzards: Declarations and Damages

As a result of the twenty-three blizzards resulting in presidential emergency or disaster declarations, approximately 64 percent, or 672 of 1,055 counties in the study region, experienced at least one county declaration in 42 winter seasons. In addition, the total number of counties declared (could be multiple declarations per storm or season) increased from 378 in Period I to 974 in Period II, a statistically significant increase of 157.7 percent, $p = 0.029$, $\alpha = 0.05$.

Most of the federal declarations in Time Period I occurred in the eastern portion of the study area with Michigan and Ohio having all counties declared as a result of the January 26, 1978, blizzard; in contrast, a great majority of the declarations issued during Time Period II were located in the north and west regions of the study area. South Dakota and North Dakota saw all counties declared during Time Period II. Many of the North Dakota declarations were issued as a result of the blizzards (and subsequent flooding) in and around the Red River of the North in April, 1997. In connection to the federal county declaration process, it was thought that some of the county declarations may have been politically driven and given according to a set of factors not related to the specific regions most affected by certain blizzards and most deserving of monetary assistance.

Based on constant 2008 US dollars, damages for the 23 blizzards resulting in federal declarations showed increases in losses over time. This largely was due to the 1997 flooding in eastern North Dakota and northwestern Minnesota. The 42-year damage estimates for these two states (~ $563 million in North Dakota and ~ $438 million in Minnesota) suggested that the blizzard damages were mixed in with damages related to the subsequent flooding events in mid-April, so it was difficult to delineate the degree of loss related to actual blizzard events. The total price tag for the April 5-6, 1997, blizzard (flood) event across the region was nearly $980 million (2008 US dollars). For comparison, the median damage estimate (based on 18 of 23 blizzards) that resulted in either emergency or disaster declarations was approximately 8.4 million. The median state damage total for 18 extreme Midwestern blizzards was approximately 85 million. From these median damage estimates, it becomes obvious that aggregate damages, those declarations that include other items besides blizzards such as flooding, create damage estimates well beyond what might be considered accurate for Midwestern blizzards occurring between September 1, 1966, and May 31, 2008.

6.2 Potential of Research

This study showed that extreme blizzards may be changing in the face of climate change, although to date the changes as measured are not statistically significant. An outcome of this research also suggested that storm track patterns present challenges and need to be studied in-depth on regional and local scales to ascertain how these Midwestern snowstorms will continue to change in the future. Only through more small or large-scale studies can geographers hope to understand the temporal and spatial nuances these storms will continue to display over time.

Continuation of this research has the potential to be used in assessing the future regions most affected by anomalous blizzards in the Midwest and other regions of the country. By getting an idea of how, where, and when these storms change in the future, the allocation of resources in time of need will be able to be assessed based on blizzard hazards and where the need is acute rather than perceived or provided based on political decisions and desires which may not be well-connected to Midwestern blizzard climatology and subsequent hazards.

6.3 Possibilities for Future Study

There are many directions this research could go in the future. By dividing the 145 storm tracks presented here into transects and following a similar methodology, it would be possible to get more detailed information regarding these storms. A second idea for future research would be to broaden the scope of snowstorms included by either relaxing the minimum central pressure criteria or lengthening the study to 50 years or longer as data becomes available or time passes beyond the end point of May 31, 2008. A third idea that would be a bit more challenging would be to try and delineate the contribution of lake effect snow in blizzard impacts across the Upper Lakes. Lastly, the template developed for this study could be applied to study blizzards, snowstorms, or other types of storms not only in the Midwest but across the United States.

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Appendix 1: Latitude and Longitude Start and End Points for Storm Tracks

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 1	-101.223	-83.931	248.6	2
(11/26-28/66)	37.0	43.780		
	Abs X Dist:	Abs Y Dist:		
	17.292	6.783		
Azimuth 2	-104.0	-84.390	258.4	2
(1/6-7/67)	41.644	45.660		
	Abs X Dist:	Abs Y Dist:		
	19.664	4.016		
Azimuth 3	-104.0	-85.025	271.8	3
(1/16-17/67)	47.254	46.662		
	Abs X Dist:	Abs Y Dist:		
	19.21	0.592		
Azimuth 4	-104.0	-83.353	262.5	2
(4/16-18/67)	42.424	45.152		
	Abs X Dist:	Abs Y Dist:		
	20.702	2.728		
Azimuth 5	-102.026	-88.521	238.8	2
(4/30/67-5/2/67)	39.953	48.148		
	Abs X Dist:	Abs Y Dist:		
	13.53	8.195		
Azimuth 6	-104.0	-99.567	220.9	1
(12/17-18/67)	43.817	49.0		
	Abs X Dist:	Abs Y Dist:		
	4.492	5.183		
Azimuth 7	-102.026	-84.058	252.2	2
(4/3-4/68)	40.323	46.091		
	Abs X Dist:	Abs Y Dist:		
	17.99	5.76		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 8 (4/21-24/68)	-102.026 38.456	-86.437 46.570	242.5	2
	Abs X Dist: 15.61	Abs Y Dist: 8.114		
Azimuth 9 (12/4-5/68)	-93.461 48.574	-85.610 46.013	288.1	3
	Abs X Dist: 7.851	Abs Y Dist: 2.561		
Azimuth 10 (12/12-13/68)	-104.0 42.243	-84.857 46.462	257.6	2
	Abs X Dist: 19.198	Abs Y Dist: 4.219		
Azimuth 11 (12/18-20/68)	-99.898 37.0	-83.317 45.105	243.9	2
	Abs X Dist: 16.581	Abs Y Dist: 8.11		
Azimuth 12 (12/22-23/68)	-102.026 38.128	-85.673 46.684	242.4	2
	Abs X Dist: 16.373	Abs Y Dist: 8.556		
Azimuth 13 (12/27-28/68)	-96.189 37.0	-83.295 41.923	249.1	2
	Abs X Dist: 12.894	Abs Y Dist: 4.924		
Azimuth 14 (1/8-9/69)	-104.0 44.771	-83.580 44.132	271.8	3
	Abs X Dist: 20.48	Abs Y Dist: 0.639		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 15 (4/26-27/69)	-104.0 44.918	-88.448 46.923	262.7	2
	Abs X Dist: 15.612	Abs Y Dist: 2.005		
Azimuth 16 (4/1-2/70)	-91.307 36.5	-83.314 41.674	237.0	2
	Abs X Dist: 7.993	Abs Y Dist: 5.184		
Azimuth 17 (11/19-21/70)	-97.570 37.0	-84.214 46.308	235.1	2
	Abs X Dist: 13.356	Abs Y Dist: 9.311		
Azimuth 18 (1/3-4/71)	-95.805 37.0	-84.582 46.420	230.0	2
	Abs X Dist: 11.223	Abs Y Dist: 9.422		
Azimuth 19 (1/25-26/71)	-104.0 45.164	-83.604 44.066	273.1	3
	Abs X Dist: 20.44	Abs Y Dist: 1.098		
Azimuth 20 (2/4-5/71)	-94.979 37.0	-86.913 46.473	220.4	1
	Abs X Dist: 8.66	Abs Y Dist: 9.473		
Azimuth 21 (2/18-20/71)	-102.026 38.050	-82.516 43.234	255.1	2
	Abs X Dist: 19.529	Abs Y Dist: 5.184		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 22 (2/22-23/71)	-93.780 36.5	-82.514 43.223	239.1	2
	Abs X Dist: 11.266	Abs Y Dist: 6.733		
Azimuth 23 (2/25-27/71)	-104.0 46.753	-89.839 48.006	265.0	2
	Abs X Dist: 14.208	Abs Y Dist: 1.253		
Azimuth 24 (3/6-7/71)	-96.264 37.0	-83.150 42.206	248.3	2
	Abs X Dist: 13.114	Abs Y Dist: 5.207		
Azimuth 25 (3/17-19/71)	-102.026 38.360	-82.536 43.335	255.7	2
	Abs X Dist: 19.51	Abs Y Dist: 4.975		
Azimuth 26 (4/1-2/71)	-102.026 38.894	-89.679 46.832	237.3	2
	Abs X Dist: 12.369	Abs Y Dist: 7.938		
Azimuth 27 (1/12/72)	-104.0 45.615	-86.712 46.462	267.2	2
	Abs X Dist: 17.335	Abs Y Dist: 0.847		
Azimuth 28 (2/17-18/72)	-103.611 49.0	-83.427 45.059	281.0	3
	Abs X Dist: 20.184	Abs Y Dist: 3.941		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 29 (3/6-7/72)	-102.536 49.0	-87.968 47.461	276.0	3
	Abs X Dist: 14.568	Abs Y Dist: 1.539		
Azimuth 30 (12/29-31/72)	-99.8 37.0	-90.181 48.111	220.9	1
	Abs X Dist: 9.619	Abs Y Dist: 11.116		
Azimuth 31 (3/14-15/73)	-102.026 40.240	-87.871 46.901	244.8	2
	Abs X Dist: 14.178	Abs Y Dist: 6.661		
Azimuth 32 (3/16-17/73)	-83.457 38.666	-80.517 41.446	226.0	2
	Abs X Dist: 2.875	Abs Y Dist: 2.78		
Azimuth 33 (4/8-10/73)	-92.747 36.5	-82.445 43.033	237.6	2
	Abs X Dist: 10.302	Abs Y Dist: 6.543		
Azimuth 34 (12/4-5/73)	-95.944 37.0	-84.043 45.496	234.5	2
	Abs X Dist: 11.901	Abs Y Dist: 8.496		
Azimuth 35 (12/12-13/73)	-104.0 44.440	-80.522 41.183	277.9	3
	Abs X Dist: 23.538	Abs Y Dist: 3.257		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 36 (2/21-22/74)	-94.201 36.5	-82.579 43.560	238.7	2
	Abs X Dist: 11.622	Abs Y Dist: 7.069		
Azimuth 37 (1/10-11/75)	-102.026 37.850	-90.938 48.228	226.9	2
	Abs X Dist: 11.106	Abs Y Dist: 10.378		
Azimuth 38 (1/24-25/75)	-100.918 49.0	-83.919 45.489	281.7	3
	Abs X Dist: 16.999	Abs Y Dist: 3.511		
Azimuth 39 (2/23-25/75)	-90.023 36.0	-87.370 46.508	194.2	1
	Abs X Dist: 2.653	Abs Y Dist: 10.512		
Azimuth 40 (3/23-25/75)	-104.0 41.599	-82.864 42.529	267.5	2
	Abs X Dist: 21.191	Abs Y Dist: 0.93		
Azimuth 41 (3/27-28/75)	-102.026 39.455	-95.837 49.0	213.1	1
	Abs X Dist: 6.212	Abs Y Dist: 9.545		
Azimuth 42 (11/9-10/75)	-101.071 37.0	-87.335 46.507	235.5	2
	Abs X Dist: 13.736	Abs Y Dist: 9.457		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 43 (3/19-20/76)	-104.0 46.841	-94.563 48.714	258.8	2
	Abs X Dist: 9.484	Abs Y Dist: 1.873		
Azimuth 44 (1/26-28/77)	-83.604 45.356	-82.583 41.403	345.0	4
	Abs X Dist: 1.57	Abs Y Dist: 3.953		
Azimuth 45 (3/11-13/77)	-102.026 37.856	-90.117 46.651	233.6	2
	Abs X Dist: 11.927	Abs Y Dist: 8.795		
Azimuth 46 (3/28-30/77)	-102.026 40.121	-85.020 46.568	249.3	2
	Abs X Dist: 17.03	Abs Y Dist: 6.447		
Azimuth 47 (11/8-10/77)	-98.238 37.0	-90.631 46.615	218.3	1
	Abs X Dist: 7.607	Abs Y Dist: 9.616		
Azimuth 48 (11/19-21/77)	-102.026 40.914	-93.030 48.627	229.5	2
	Abs X Dist: 9.17	Abs Y Dist: 7.713		
Azimuth 49 (1/26/78)	-83.707 38.633	-81.850 41.497	213.0	1
	Abs X Dist: 1.857	Abs Y Dist: 2.864		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 50	-98.691	-80.903	261.6	2
(4/17-19/78)	37.0	39.613		
	Abs X Dist:	Abs Y Dist:		
	17.788	2.615		
Azimuth 51	-94.633	-82.472	243.3	2
(1/13-14/79)	36.739	42.857		
	Abs X Dist:	Abs Y Dist:		
	12.15	6.118		
Azimuth 52	-104.0	-80.898	287.3	3
(1/22-24/79)	46.842	39.615		
	Abs X Dist:	Abs Y Dist:		
	23.149	7.227		
Azimuth 53	-100.181	-82.519	250.5	2
(3/22-24/79)	37.0	43.249		
	Abs X Dist:	Abs Y Dist:		
	17.662	6.251		
Azimuth 54	-102.026	-96.891	208.0	1
(4/11-13/79)	39.307	49.0		
	Abs X Dist:	Abs Y Dist:		
	5.157	9.693		
Azimuth 55	-104.0	-88.444	261.9	2
(1/5-7/80)	44.730	46.956		
	Abs X Dist:	Abs Y Dist:		
	15.616	2.226		
Azimuth 56	-104.0	-91.693	254.9	2
(1/10-11/80)	44.773	48.114		
	Abs X Dist:	Abs Y Dist:		
	12.367	3.341		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 57 (3/21/80)	-80.517 38.663	-80.520 41.450	220.1	1
	Abs X Dist: 2.347	Abs Y Dist: 2.787		
Azimuth 58 (11/30/81-12/1/81)	-98.252 37.0	-87.546 46.704	227.8	2
	Abs X Dist: 10.706	Abs Y Dist: 9.705		
Azimuth 59 (1/3-4/82)	-92.441 36.5	-83.570 44.164	229.1	2
	Abs X Dist: 8.871	Abs Y Dist: 7.673		
Azimuth 60 (1/22-23/82)	-102.007 37.0	-86.178 46.663	238.6	2
	Abs X Dist: 15.829	Abs Y Dist: 9.674		
Azimuth 61 (3/29-30/82)	-104.0 44.75	-94.696 48.922	246.0	2
	Abs X Dist: 9.364	Abs Y Dist: 4.172		
Azimuth 62 (4/2-3/82)	-104.0 43.666	-84.282 46.433	262.0	2
	Abs X Dist: 19.777	Abs Y Dist: 2.767		
Azimuth 63 (10/8-11/82)	-102.026 38.779	-92.354 48.225	225.7	2
	Abs X Dist: 9.694	Abs Y Dist: 9.446		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 64 (11/11-12/82)	-102.026 39.440	-86.874 46.446	245.2	2
	Abs X Dist: 15.175	Abs Y Dist: 7.006		
Azimuth 65 (12/27-28/82)	-97.137 37.0	-85.020 46.560	231.7	2
	Abs X Dist: 12.117	Abs Y Dist: 9.56		
Azimuth 66 (2/1-3/83)	-92.230 36.5	-82.584 43.585	233.7	2
	Abs X Dist: 9.646	Abs Y Dist: 7.094		
Azimuth 67 (3/5-9/83)	-100.510 37.0	-80.872 39.665	262.3	2
	Abs X Dist: 19.638	Abs Y Dist: 2.667		
Azimuth 68 (3/20-21/83)	-83.361 38.649	-80.607 40.343	238.4	2
	Abs X Dist: 2.754	Abs Y Dist: 1.694		
Azimuth 69 (4/12-14/83)	-102.026 38.159	-87.913 46.910	238.2	2
	Abs X Dist: 14.133	Abs Y Dist: 8.751		
Azimuth 70 (11/27-29/83)	-95.483 37.0	-88.026 46.912	217.0	1
	Abs X Dist: 7.457	Abs Y Dist: 9.911		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 71 (4/26-27/84)	-102.026 40.209	-96.428 49.0	212.6	1
	Abs X Dist: 5.621	Abs Y Dist: 8.791		
Azimuth 72 (4/29-30/84)	-98.889 37.0	-86.941 46.492	231.5	2
	Abs X Dist: 11.948	Abs Y Dist: 9.494		
Azimuth 73 (11/25-27/84)	-103.010 41.0	-93.783 48.512	230.8	2
	Abs X Dist: 9.227	Abs Y Dist: 7.513		
Azimuth 74 (3/3-5/85)	-102.026 38.579	-83.861 45.455	249.3	2
	Abs X Dist: 18.186	Abs Y Dist: 6.876		
Azimuth 75 (3/10-12/85)	-102.026 39.633	-82.796 44.025	257.2	2
	Abs X Dist: 19.254	Abs Y Dist: 4.392		
Azimuth 76 (12/26-27/85)	-95.152 49.358	-92.465 48.346	290.6	3
	Abs X Dist: 2.687	Abs Y Dist: 1.012		
Azimuth 77 (4/13-15/86)	-102.026 39.728	-82.561 43.466	259.1	2
	Abs X Dist: 19.489	Abs Y Dist: 3.738		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 78 (11/7-8/86)	-102.026 40.449	-94.267 48.685	223.4	1
	Abs X Dist: 7.781	Abs Y Dist: 8.236		
Azimuth 79 (2/7-8/87)	-95.155 49.198	-82.630 43.808	293.3	3
	Abs X Dist: 12.525	Abs Y Dist: 5.39		
Azimuth 80 (12/14-16/87)	-91.516 36.5	-83.438 44.945	223.7	1
	Abs X Dist: 8.78	Abs Y Dist: 8.454		
Azimuth 81 (1/19-20/88)	-102.026 37.143	-83.556 46.043	244.3	2
	Abs X Dist: 18.483	Abs Y Dist: 8.90		
Azimuth 82 (3/11-13/88)	-102.026 39.593	-83.566 44.175	256.1	2
	Abs X Dist: 18.484	Abs Y Dist: 4.582		
Azimuth 83 (11/15-16/88)	-102.026 38.373	-90.115 48.106	230.8	2
	Abs X Dist: 11.931	Abs Y Dist: 9.733		
Azimuth 84 (11/26-27/88)	-99.545 37.0	-87.328 46.507	232.1	2
	Abs X Dist: 12.217	Abs Y Dist: 9.50		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 85 (1/31/89-2/1/89)	-104.0 45.598	-83.537 46.016	268.8	2
	Abs X Dist: 20.51	Abs Y Dist: 0.418		
Azimuth 86 (3/2-4/89)	-102.026 37.428	-83.302 44.603	249.0	2
	Abs X Dist: 18.74	Abs Y Dist: 7.175		
Azimuth 87 (3/13-14/89)	-104.0 42.703	-83.392 44.904	263.9	2
	Abs X Dist: 20.664	Abs Y Dist: 2.201		
Azimuth 88 (11/14-16/89)	-95.301 37.0	-83.926 43.838	239.0	2
	Abs X Dist: 11.375	Abs Y Dist: 6.837		
Azimuth 89 (1/24-25/90)	-94.289 36.5	-83.464 45.314	230.8	2
	Abs X Dist: 10.825	Abs Y Dist: 8.824		
Azimuth 90 (3/14-16/90)	-96.184 37.0	-95.60 49.0	182.8	1
	Abs X Dist: 0.584	Abs Y Dist: 12.001		
Azimuth 91 (5/8-10/90)	-102.026 38.183	-84.064 45.497	247.9	2
	Abs X Dist: 17.982	Abs Y Dist: 7.314		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 92 (10/16-18/90)	-104.0 42.778	-84.191 46.266	260.0	2
	Abs X Dist: 19.865	Abs Y Dist: 3.488		
Azimuth 93 (3/11-13/91)	-102.026 40.362	-88.136 37.584	281.3	3
	Abs X Dist: 13.912	Abs Y Dist: 2.778		
Azimuth 94 (3/22-23/91)	-102.026 39.626	-86.433 45.779	248.5	2
	Abs X Dist: 15.617	Abs Y Dist: 6.153		
Azimuth 95 (3/27/91)	-102.026 39.612	-86.906 46.468	245.6	2
	Abs X Dist: 15.144	Abs Y Dist: 6.856		
Azimuth 96 (10/31/91-11/2/91)	-94.508 36.5	-89.332 46.873	206.5	1
	Abs X Dist: 5.176	Abs Y Dist: 10.383		
Azimuth 97 (11/29-30/91)	-102.026 37.247	-87.776 46.871	236.0	2
	Abs X Dist: 14.264	Abs Y Dist: 9.624		
Azimuth 98 (1/14/92)	-84.229 38.813	-80.517 41.461	234.5	2
	Abs X Dist: 3.709	Abs Y Dist: 2.648		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 99 (4/18-20/92)	-104.014 49.0	-94.407 36.5	322.5	4
	Abs X Dist: 9.607	Abs Y Dist: 12.51		
Azimuth 100 (11/1-3/92)	-98.525 37.0	-90.135 48.110	217.1	1
	Abs X Dist: 8.39	Abs Y Dist: 11.112		
Azimuth 101 (2/20-22/93)	-102.026 39.433	-83.484 41.725	263.0	2
	Abs X Dist: 18.565	Abs Y Dist: 2.292		
Azimuth 102 (4/14-16/94)	-101.877 37.0	-87.776 46.872	235.0	2
	Abs X Dist: 14.101	Abs Y Dist: 9.881		
Azimuth 103 (4/25-26/94)	-104.0 41.561	-87.386 46.524	253.4	2
	Abs X Dist: 16.669	Abs Y Dist: 4.963		
Azimuth 104 (11/17-18/94)	-104.0 43.255	-94.375 48.71	240.6	2
	Abs X Dist: 9.683	Abs Y Dist: 5.455		
Azimuth 105 (11/27-28/94)	-102.026 38.458	-87.829 46.888	239.3	2
	Abs X Dist: 14.218	Abs Y Dist: 8.43		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 106 (2/9-10/95)	-99.659 49.0	-91.194 47.332	281.1	3
	Abs X Dist: 8.465	Abs Y Dist: 1.668		
Azimuth 107 (4/17-19/95)	-99.172 37.0	-84.717 46.463	236.8	2
	Abs X Dist: 14.455	Abs Y Dist: 9.466		
Azimuth 108 (11/26-27/95)	-102.026 38.467	-82.826 42.581	257.9	2
	Abs X Dist: 19.221	Abs Y Dist: 4.114		
Azimuth 109 (1/17-19/96)	-99.564 37.0	-84.337 46.487	238.1	2
	Abs X Dist: 15.227	Abs Y Dist: 9.492		
Azimuth 110 (1/26-27/96)	-96.621 37.0	-84.376 45.661	234.7	2
	Abs X Dist: 12.245	Abs Y Dist: 8.661		
Azimuth 111 (2/10-11/96)	-97.202 49.0	-84.204 46.291	281.8	3
	Abs X Dist: 12.998	Abs Y Dist: 2.709		
Azimuth 112 (3/23-25/96)	-102.026 38.026	-85.003 46.768	242.8	2
	Abs X Dist: 17.42	Abs Y Dist: 8.742		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 113 (4/25/96)	-99.45 49.0	-84.266 46.404	279.7	3
	Abs X Dist: 15.184	Abs Y Dist: 2.596		
Azimuth 114 (12/23-24/96)	-99.147 37.0	-83.542 45.355	241.8	2
	Abs X Dist: 15.605	Abs Y Dist: 8.358		
Azimuth 115 (1/3-5/97)	-101.974 37.0	-84.054 45.497	244.6	2
	Abs X Dist: 17.92	Abs Y Dist: 8.507		
Azimuth 116 (1/9-10/97)	-88.139 37.469	-83.299 44.778	213.5	1
	Abs X Dist: 4.84	Abs Y Dist: 7.309		
Azimuth 117 (2/26-27/97)	-94.618 36.521	-82.472 42.89	242.3	2
	Abs X Dist: 12.146	Abs Y Dist: 6.369		
Azimuth 118 (4/5-6/97)	-102.026 40.697	-91.834 48.217	233.6	2
	Abs X Dist: 10.209	Abs Y Dist: 7.52		
Azimuth 119 (2/25-27/98)	-104.0 41.669	-87.781 42.699	266.4	2
	Abs X Dist: 16.273	Abs Y Dist: 1.03		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 120 (3/8-9/98)	-92.422 36.5	-83.092 41.59	241.3	2
	Abs X Dist: 9.33	Abs Y Dist: 5.099		
Azimuth 121 (11/9-10/98)	-102.026 37.83	-90.28 48.106	228.9	2
	Abs X Dist: 11.764	Abs Y Dist: 10.276		
Azimuth 122 (1/17-18/99)	-100.057 49.0	-88.475 46.86	280.5	3
	Abs X Dist: 11.582	Abs Y Dist: 2.14		
Azimuth 123 (2/25-26/00)	-104.0 42.395	-90.859 48.247	246.1	2
	Abs X Dist: 13.196	Abs Y Dist: 5.852		
Azimuth 124 (3/27-28/00)	-85.481 46.681	-81.81 41.495	324.7	4
	Abs X Dist: 3.671	Abs Y Dist: 5.186		
Azimuth 125 (11/1-2/00)	-102.026 40.976	-97.162 49.0	211.3	1
	Abs X Dist: 4.886	Abs Y Dist: 8.024		
Azimuth 126 (12/15-17/00)	-102.026 37.129	-82.678 43.888	250.8	2
	Abs X Dist: 19.361	Abs Y Dist: 6.759		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 127 (1/29-30/01)	-94.633 36.838	-83.441 45.039	233.7	2
	Abs X Dist: 11.18	Abs Y Dist: 8.201		
Azimuth 128 (2/24-25/01)	-102.026 37.213	-90.718 46.642	230.2	2
	Abs X Dist: 11.322	Abs Y Dist: 9.429		
Azimuth 129 (4/11-12/01)	-102.026 38.981	-87.867 46.9	240.8	2
	Abs X Dist: 14.182	Abs Y Dist: 7.919		
Azimuth 130 (10/24-25/01)	-104.0 46.529	-92.081 46.795	268.7	2
	Abs X Dist: 11.966	Abs Y Dist: 0.266		
Azimuth 131 (3/14-15/02)	-102.026 37.0	-84.259 46.392	242.1	2
	Abs X Dist: 17.778	Abs Y Dist: 9.402		
Azimuth 132 (2/3-4/03)	-97.697 37.0	-84.368 46.484	234.6	2
	Abs X Dist: 13.329	Abs Y Dist: 9.486		
Azimuth 133 (1/12/05)	-102.026 37.166	-87.349 46.507	237.5	2
	Abs X Dist: 14.69	Abs Y Dist: 9.341		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 134 (3/6-7/05)	-97.083 49.0	-84.24 45.641	284.7	3
	Abs X Dist: 12.843	Abs Y Dist: 3.359		
Azimuth 135 (11/15-16/05)	-95.767 37.0	-85.038 46.494	228.5	2
	Abs X Dist: 10.729	Abs Y Dist: 9.496		
Azimuth 136 (11/27-29/05)	-102.026 37.222	-91.022 46.907	228.7	2
	Abs X Dist: 11.18	Abs Y Dist: 9.685		
Azimuth 137 (2/4-5/06)	-82.554 38.401	-81.699 41.513	195.4	1
	Abs X Dist: 0.855	Abs Y Dist: 3.112		
Azimuth 138 (4/6-7/06)	-104.0 42.37	-82.421 42.971	268.4	2
	Abs X Dist: 21.634	Abs Y Dist: 0.601		
Azimuth 139 (2/24-25/07)	-102.026 38.943	-82.513 42.648	259.3	2
	Abs X Dist: 19.536	Abs Y Dist: 3.705		
Azimuth 140 (2/28/07-3/3/07)	-102.026 37.515	-83.319 44.522	249.5	2
	Abs X Dist: 18.724	Abs Y Dist: 7.007		

Azimuth Name	Start Pt (X,Y)	End Pt (X,Y)	Azimuth	Storm Track Class
Azimuth 141 (4/10-12/07)	-104.0 45.727	-83.928 43.813	275.4	3
	Abs X Dist: 20.12	Abs Y Dist: 1.914		
Azimuth 142 (12/22-23/07)	-97.103 37.0	-86.126 46.666	228.6	2
	Abs X Dist: 10.977	Abs Y Dist: 9.666		
Azimuth 143 (2/17-18/08)	-94.633 36.563	-84.032 45.496	229.8	2
	Abs X Dist: 10.587	Abs Y Dist: 8.933		
Azimuth 144 (4/10-11/08)	-97.819 37.0	-84.268 45.65	237.4	2
	Abs X Dist: 13.551	Abs Y Dist: 8.651		
Azimuth 145 (5/1-3/08)	-99.526 37.0	-88.247 46.908	228.7	2
	Abs X Dist: 11.279	Abs Y Dist: 9.913		

Appendix 2: Method for Determining Storms with Federal Declarations

Sources: PERI, FEMA, Storm Data, Academic OneFile, NOAA Daily Weather Maps, and ArcGIS 9.3

Definition: For this study, a federal declaration is defined as either a federal disaster declaration or a federal emergency declaration. This definition does not include federal declarations due to secondary effects due to snowstorms such as ice jams, snowmelt, and flooding.

Step 1: I noted the federal declarations that were given for ice storms, snowstorms, and blizzards for the twelve states in my study region using PERI and FEMA websites (select years between 1976 and 2008 had declarations).

Step 2: For 1998-2008, it was easy to match up the storm events with the declarations because each declaration that was noted also referred to the storm dates for which the declaration was given. For storms prior to 1998, it was more difficult to match the storm event to the declaration because the various declarations are not always given immediately after a storm occurs. Sometimes it may be several months before a declaration is put forth because all the myriad damages may not be immediately realized.

Step 3: To offset the ambiguity in matching some of the older declarations to a certain storm event in time and space (more recent storms gave an incident date, defined as the temporal storm reference for a specific declaration), I first attempted to get some answers from the Storm Data publications at Anschutz Library, KU. By using this publication, I hoped to match my blizzards to federal declarations cited in Storm Data.

Step 4: I tired to match any presidential declarations or counties suffering extreme damage as cited in Storm Data to county listings associated with presidential declarations given on the PERI website.

Step 5: I tried to correlate the spatial relationship of counties revealed in Step 4 to a given blizzard/storm event (of the 145 storms in my study area). Often I would need to refer back to the PERI website to cross-correlate information to a specific storm event as described in the Storm Notes in Storm Data. At times, I also referred to the storm track that was previously digitized in ArcGIS to correlate the spatial proximity of declared disaster counties to the path of the snowstorm for further confirmation of a correct match.

Step 6: I rechecked all of the state declarations. I also checked the disaster declaration numbers (as cited in PERI) between states too so I did not omit counties in another state for storms that were very strong and crossed several borders (this was easy to recognize because the declarations are given in sequence and adjacent numbers indicated the same snowstorm).

Step 7: I re-checked 1966-1975 (PERI website) for any omissions of ice storms, snowstorms, or blizzards resulting in disaster declarations.

Step 8: Produced the final disaster declaration list for blizzards with 992 mb. These select storms (as mentioned in Appendix 5) will be used in the statistics spreadsheet.

Appendix 3: Methodology for Creating Hazard Areas from 145 Storm Tracks

Step 1: Add Storm Track

Step 2: Make Whole Buffer (50 km buffer unclipped)

Step 3: Make new clipped buffer (50 km buffer)

Step 4: Make new hazard zone areas

4A1: Select all counties (1055 counties)

4A2: Remove from selection Haz Area X

4A3: Switch Selection (Now Haz Area X should be selected)

4A4: Select from features in 4A3 that intersect 50 km storm track buffer

4B: Create shapefile from selected features

4C: Update Midwest Counties attribute table (flagging of counties).

4D: Erase any overlaps in county layers. New Layer name: Hazard Area X

4E: Make shapefile in 4B into new Haz layer (so the name can be changed to Haz Area X)

Step 5: Repeat Step 4 as needed to update all county polygons.

Appendix 4: Complete Listing of Blizzards Included in Study

<u>1966</u>
November 26-28

<u>1967</u>
January 6-7
January 16-17
April 16-18
April 30-May 2
December 17-18

<u>1968</u>
April 3-4
April 21-24
December 4-5
December 12-13
December 18-20
December 22-23
December 27-28

<u>1969</u>
January 8-9
April 26-27

<u>1970</u>
April 1-2
November 19-21

<u>1971</u>
January 3-4
January 25-26
February 4-5
February 18-20
February 22-23
February 25-27
March 6-7
March 17-19
April 1-2

<u>1972</u>
January 12
February 17-18
March 6-7
December 29-31

1973
March 14-15
March 16-17
April 8-10
December 4-5
December 12-13

1974
February 21-22

1975
January 10-11
January 24-25
February 23-25
March 23-25
March 27-28
November 9-10

1976
March 19-20

1977
January 26-28
March 11-13
March 28-30
November 8-10
November 19-21

1978
January 26
April 17-19

1979
January 13-14
January 22-24
March 22-24
April 11-13

1980
January 5-7
January 10-11
March 21

1981
Nov 30-Dec 1

1982
January 3-4
January 22-23
March 29-30
April 2-3
October 8-11
November 11-12
December 27-28

1983
February 1-3
March 5-9
March 20-21
April 12-14
November 27-29

1984
April 26-27
April 29-30
November 25-27

1985
March 3-5
March 10-12
December 26-27

1986
April 13-15
November 7-8

1987
February 7-8
December 14-16

1988
January 19-20
March 11-13
November 15-16
November 26-27

1989
January 31-February 1
March 2-4
March 13-14
November 14-16

1990
January 24-25
March 14-16
May 8-10
October 16-18

1991
March 11-13
March 22-23
March 27
October 31-November 2
November 29-30

1992
January 14
April 18-20
November 1-3

1993
February 20-22

1994
April 14-16
April 25-26
November 17-18
November 27-28

1995
February 9-10
April 17-19
November 26-27

1996
January 17-19
January 26-27
February 10-11
March 23-25
April 25
December 23-24

1997
January 3-5
January 9-10
February 26-27
April 5-6

1998
February 25-27
March 8-9
November 9-10

1999
January 17-18

2000
February 25-26
March 27-28
November 1-2
December 15-17

2001
January 29-30
February 24-25
April 11-12
October 24-25

2002
March 14-15

2003
February 3-4

2004
No Blizzards

2005
January 12
March 6-7
November 15-16
November 27-29

2006
February 4-5
April 6-7

2007
February 24-25
Feb 28-Mar 3
April 10-12
December 22-23

2008
February 17-18
April 10-11
May 1-3

Appendix 5:
States, Declaration Numbers, Corresponding Storms, and Federally Declared Counties

Illinois
3068 (1/13-14/79)
Lake, Bureau, Carroll, Cook, DeKalb, DuPage, Grundy, Henry, Jo Daviess, Kane, Boone, La Salle, Winnebago, Lee, Marshall, McHenry, Mercer, Ogle, Peoria, Putnam, Stephenson, Whiteside, Will, Kendall

860 (1/24-25/90)
Vermilion, Piatt, Moultrie, McLean, Livingston, Iroquois, Ford, Edgar, Douglas, Champaign

3161 (12/15-17/00)
La Salle, Bureau, Cook, De Witt, DuPage, Ford, Fulton, Grundy, Henderson, Henry, Iroquois, Kane, Boone, Kendall, Winnebago, Lake, Livingston, Marshall, McDonough, McHenry, McLean, Menard, Ogle, Peoria, Stark, Will, Kankakee

Indiana
3028 (1/26-28/77)
Franklin, Adams, Lagrange, Kosciusko, Jennings, Jay, Henry, Harrison, Madison, Fulton, Monroe, Fayette, Elkhart, Clay, Cass, Carroll, Boone, Blackford, Benton, Grant, Rush, Wells, Warren, Vigo, Tipton, Switzerland, Sullivan, Steuben, Lake, St. Joseph, Whitley, Ripley, Randolph, Pulaski, Posey, Pike, Perry, Parke, Newton, Starke

3056 (1/26/78)
Lagrange

899 (3/11-13/91)
Jasper, Blackford, Boone, Carroll, Cass, Clinton, Delaware, Fayette, Grant, Hamilton, Hancock, Benton, Howard, White, Madison, Miami, Montgomery, Newton, Randolph, Tippecanoe, Tipton, Union, Warren, Wayne, Wells, Henry

1217 (3/8-9/98)
Starke, St. Joseph, Pulaski, Porter, Newton, LaPorte, Lake, Jasper, Benton

3162 (12/15-17/00)
Lake, Allen, Benton, Carroll, Cass, DeKalb, Elkhart, Fulton, Grant, Howard, Huntington, Jasper, Kosciusko, Adams, Lagrange, Whitley, Marshall, Miami, Newton, Noble, Porter, Pulaski, St. Joseph, Starke, Steuben, Wabash, Wells, White, La Porte

1573 (1/12/05)
Howard, Franklin, Fulton, Gibson, Grant, Greene, Hamilton, Hancock, Harrison, Lake, Henry, Fayette, Huntington, Jackson, Jasper, Jay, Jennings, Johnson, Knox, Adams, Hendricks, Clinton, Allen, Bartholomew, Benton, Blackford, Boone, Brown, Carroll, Cass, Fountain, Clay, Floyd, Crawford, Daviess, Dearborn, Decatur, DeKalb, Delaware, Dubois, Elkhart, LaPorte, Clark, Vermillion, Rush, Scott, Shelby, St. Joseph, Starke, Sullivan, Tippecanoe, Tipton, Kosciusko,

Vanderburgh, Putnam, Vigo, Wabash, Warren, Warrick, Washington, Wayne, Wells, White, Union, Noble, Lawrence, Madison, Marion, Marshall, Martin, Miami, Monroe, Montgomery, Ripley, Newton, Randolph, Orange, Owen, Parke, Perry, Pike, Porter, Posey, Pulaski, Whitley, Morgan

Iowa

928 (10/31/91-11/2/91)
Clay, Adair, Hancock, Hamilton, Guthrie, Greene, Fremont, Franklin, Emmet, Humboldt, Dallas, Ida, Cherokee, Cerro Gordo, Cass, Carroll, Calhoun, Buena Vista, Boone, Audubon, Adams, Dickinson, Plymouth, Worth, Woodbury, Winnebago, Webster, Union, Taylor, Shelby, Sac, Hardin, Pocahontas, Wright, Palo Alto, Page, Osceola, O'Brien, Montgomery, Mitchell, Mills, Madison, Kossuth, Ringgold

1191 (2/26-27/97, 4/5-6/97)
Warren, Union, Poweshiek, Pottawattamie, Polk, Mills, Marion, Mahaska, Madison, Jasper, Iowa, Clarke, Cass

1688 (2/28/07-3/3/07)
Des Moines, Iowa, Humboldt, Howard, Henry, Hardin, Hamilton, Grundy, Greene, Franklin, Benton, Fayette, Jefferson, Clinton, Chickasaw, Cedar, Calhoun, Butler, Buena Vista, Buchanan, Bremer, Boone, Black Hawk, Floyd, Mitchell, Worth, Winneshiek, Winnebago, Washington, Wapello, Van Buren, Tama, Story, Poweshiek, Polk, Jackson, Muscatine, Jasper, Marshall, Marion, Mahaska, Louisa, Linn, Lee, Keokuk, Jones, Johnson, Wright, Pocahontas

3275 (2/28/07-3/3/07)
Ida, Audubon, Buena Vista, Carroll, Cass, Cherokee, Clay, Crawford, Dickinson, Emmet, Greene, Guthrie, Hancock, Adair, Humboldt, Wright, Kossuth, Monona, O'Brien, Osceola, Palo Alto, Plymouth, Pocahontas, Pottawattamie, Sac, Shelby, Webster, Winnebago, Woodbury, Harrison

Kansas

1626 (11/27-29/05)
Phillips, Decatur, Edwards, Gove, Graham, Hodgeman, Ness, Cheyenne, Pawnee, Trego, Rawlins, Rooks, Rush, Sheridan, Sherman, Thomas, Norton

Michigan

495 (3/19-20/76)
Montcalm, Bay, Clare, Clinton, Genesee, Gladwin, Gratiot, Ionia, Isabella, Jackson, Kent, Lapeer, Macomb, Allegan, Midland, Wayne, Muskegon, Newaygo, Oakland, Oceana, Osceola, Ottawa, Roscommon, Saginaw, Sanilac, Shiawassee, St. Clair, Tuscola, Mecosta

3030 (1/26-28/77)
Van Buren, Shiawassee, Sanilac, Ottawa, Oceana, Ionia, Hillsdale, Eaton, Chippewa, Cass, Barry, Allegan

3057 (1/26/78)

Huron, Eaton, Emmet, Genesee, Gladwin, Gogebic, Grand Traverse, Gratiot, Alcona, Houghton, Crawford, Ingham, Ionia, Iosco, Iron, Isabella, Jackson, Kalamazoo, Kalkaska, Hillsdale, Branch, Alger, Allegan, Alpena, Antrim, Arenac, Baraga, Barry, Bay, Dickinson, Berrien, Delta, Calhoun, Cass, Charlevoix, Cheboygan, Chippewa, Clare, Clinton, Lake, Benzie, Sanilac, Kent, Ogemaw, Ontonagon, Osceola, Oscoda, Otsego, Ottawa, Presque Isle, Oakland, Saginaw, Newaygo, Schoolcraft, Shiawassee, St. Clair, St. Joseph, Tuscola, Van Buren, Washtenaw, Wayne, Roscommon, Mason, Wexford, Lapeer, Leelanau, Lenawee, Livingston, Luce, Mackinac, Macomb, Oceana, Marquette, Keweenaw, Mecosta, Menominee, Midland, Missaukee, Monroe, Montcalm, Montmorency, Muskegon, Manistee

3160 (12/15-17/00)
Clinton, Isabella, Ionia, Ingham, Huron, Hillsdale, Gratiot, Gladwin, Allegan, Eaton, Kent, Clare, Cass, Calhoun, Branch, Berrien, Bay, Barry, Genesee, Oakland, Van Buren, Tuscola, St. Joseph, St. Clair, Shiawassee, Sanilac, Saginaw, Jackson, Osceola, Kalamazoo, Muskegon, Montcalm, Midland, Mecosta, Macomb, Livingston, Lapeer, Washtenaw, Ottawa

<u>Minnesota</u>
929 (10/31/91-11/2/91)
Waseca, Steele, Rice, Olmsted, Mower, Martin, Goodhue, Freeborn, Fillmore, Faribault, Dodge, Blue Earth

1078 (11/26-27/95)
Traverse, Swift, Stevens, Big Stone

1151 (1/3-5/97)
Yellow Medicine, Waseca, Rock, Pipestone, Nobles, Murray, Lyon, Lincoln, Jackson, Freeborn, Faribault, Cottonwood

1158 (1/9-10/97)
Grant, McLeod, Martin, Marshall, Mahnomen, Lyon, Lincoln, Le Sueur, Lake of the Woods, Lac qui Parle, Kittson, Kandiyohi, Becker, Hubbard, Nicollet, Faribault, Douglas, Cottonwood, Clearwater, Clay, Chippewa, Brown, Blue Earth, Big Stone, Benton, Beltrami, Jackson, Roseau, Wright, Wilkin, Watonwan, Waseca, Wadena, Traverse, Todd, Swift, Stevens, Steele, Stearns, Meeker, Sherburne, Murray, Rock, Renville, Redwood, Red Lake, Pope, Polk, Pipestone, Pennington, Otter Tail, Norman, Nobles, Yellow Medicine, Sibley

1175 (4/5-6/97)
Dakota, Mahnomen, Lyon, Lincoln, Le Sueur, Lake of the Woods, Lac qui Parle, Kittson, Kandiyohi, Hubbard, Houston, Hennepin, Grant, Aitkin, Douglas, Morrison, Clearwater, Clay, Chippewa, Cass, Carver, Brown, Blue Earth, Big Stone, Benton, Beltrami, Becker, Anoka, Goodhue, Scott, Wright, Winona, Wilkin, Washington, Wadena, Wabasha, Traverse, Todd, Swift, Stevens, Stearns, St. Louis, Marshall, Sherburne, McLeod, Roseau, Renville, Redwood, Red Lake, Ramsey, Pope, Polk, Pennington, Otter Tail, Norman, Nicollet, Murray, Yellow Medicine, Sibley

1622 (11/27-29/05)

Yellow Medicine, Wilkin, Traverse, Stevens, Norman, Lincoln, Lac qui Parle, Clay, Big Stone

Missouri
No Disaster Declarations

Nebraska
500 (3/19-20/76)
Merrick, Butler, Clay, Fillmore, Gage, Hall, Hamilton, Jefferson, Adams, Madison, York, Nuckolls, Platte, Polk, Saline, Saunders, Seward, Thayer, Webster, Kearney

1627 (11/27-29/05)
Lincoln, Boone, Boyd, Custer, Dawson, Dundy, Frontier, Furnas, Garfield, Gosper, Greeley, Hayes, Holt, Antelope, Knox, Wheeler, Logan, Loup, Madison, McPherson, Nance, Perkins, Phelps, Pierce, Red Willow, Rock, Valley, Wayne, Kearney

North Dakota
3061 (11/8-10/77, 11/19-21/77)
Slope, Sioux, Hettinger, Grant, Golden Valley, Emmons, Bowman, Billings, Adams

1157 (1/3-5/97, 1/9-10/97)
Dunn, McHenry, Logan, LaMoure, Kidder, Hettinger, Griggs, Grant, Grand Forks, Golden Valley, Foster, Adams, Eddy, McLean, Divide, Dickey, Cavalier, Cass, Burleigh, Burke, Bowman, Bottineau, Billings, Benson, Barnes, Emmons, Richland, Wells, Ward, Walsh, Traill, Towner, Stutsman, Steele, Stark, Slope, Sioux, Sheridan, McIntosh, Rolette, McKenzie, Renville, Ransom, Ramsey, Pierce, Pembina, Oliver, Nelson, Mountrail, Morton, Mercer, Williams, Sargent

1174 (4/5-6/97)
Dunn, McHenry, Logan, LaMoure, Kidder, Hettinger, Griggs, Grant, Grand Forks, Golden Valley, Foster, Adams, Eddy, McLean, Divide, Dickey, Cavalier, Cass, Burleigh, Burke, Bowman, Bottineau, Billings, Benson, Barnes, Emmons, Richland, Wells, Ward, Walsh, Traill, Towner, Stutsman, Steele, Stark, Slope, Sioux, Sheridan, McIntosh, Rolette, McKenzie, Renville, Ransom, Ramsey, Pierce, Pembina, Oliver, Nelson, Mountrail, Morton, Mercer, Williams, Sargent

1353 (11/1-2/00)
Williams, Towner, Ramsey, McKenzie, Golden Valley, Divide, Cavalier, Bowman, Benson

1621 (11/27-29/05)
Sargent, Richland, Ransom, Cass

Ohio
3029 (1/26-28/77)
Crawford, Huron, Holmes, Highland, Henry, Harrison, Hardin, Hancock, Greene, Fayette, Ashland, Darke, Lorain, Coshocton, Columbiana, Clinton, Clermont, Carroll, Brown, Belmont, Athens, Ashtabula, Defiance, Portage, Wayne, Washington, Van Wert, Tuscarawas, Stark,

Shelby, Seneca, Ross, Richland, Jefferson, Preble, Knox, Pickaway, Perry, Paulding, Noble, Muskingum, Miami, Medina, Marion, Lucas, Wood, Putnam

3055 (1/26/78)
Harrison, Lawrence, Franklin, Fulton, Gallia, Geauga, Greene, Guernsey, Hamilton, Fairfield, Hardin, Erie, Henry, Highland, Hocking, Holmes, Huron, Jackson, Jefferson, Knox, Adams, Hancock, Clark, Allen, Ashland, Ashtabula, Athens, Auglaize, Belmont, Brown, Butler, Fayette, Champaign, Licking, Clermont, Clinton, Columbiana, Coshocton, Crawford, Cuyahoga, Darke, Defiance, Delaware, Carroll, Trumbull, Lake, Putnam, Richland, Ross, Sandusky, Scioto, Seneca, Shelby, Portage, Summit, Pike, Tuscarawas, Union, Van Wert, Vinton, Warren, Washington, Wayne, Williams, Wood, Stark, Monroe, Logan, Lorain, Lucas, Madison, Mahoning, Marion, Medina, Meigs, Preble, Miami, Wyandot, Montgomery, Morgan, Morrow, Muskingum, Noble, Ottawa, Paulding, Perry, Pickaway, Mercer

1580 (1/12/05)
Darke, Adams, Jefferson, Huron, Holmes, Hocking, Highland, Henry, Harrison, Hardin, Hancock, Guernsey, Franklin, Fayette, Licking, Champaign, Allen, Ashland, Athens, Auglaize, Belmont, Fairfield, Carroll, Delaware, Clark, Clermont, Columbiana, Coshocton, Crawford, Logan, Brown, Perry, Wayne, Washington, Warren, Van Wert, Union, Tuscarawas, Stark, Shelby, Seneca, Scioto, Ross, Richland, Putnam, Knox, Montgomery, Lorain, Marion, Medina, Meigs, Mercer, Pike, Monroe, Pickaway, Morgan, Morrow, Muskingum, Noble, Paulding, Wyandot, Miami

<u>South Dakota</u>
1045 (11/17-18/94, 11/27-28/94)
Hyde, Brule, Buffalo, Campbell, Corson, Dewey, Edmunds, Faulk, Haakon, Aurora, Hughes, Ziebach, Jerauld, Jones, Lyman, McPherson, Potter, Stanley, Sully, Walworth, Hand

1075 (11/26-27/95)
Gregory, Beadle, Bon Homme, Brookings, Brule, Buffalo, Charles Mix, Clark, Codington, Davison, Deuel, Aurora, Grant, Tripp, Hamlin, Hanson, Hutchinson, Jerauld, Kingsbury, Lake, McCook, Miner, Roberts, Sanborn, Spink, Douglas
1156 (1/3-5/97, 1/9-10/97)
Gregory, Deuel, Dewey, Douglas, Edmunds, Fall River, Hutchinson, Grant, Custer, Haakon, Hamlin, Hand, Hanson, Harding, Aurora, Faulk, Campbell, Beadle, Bennett, Bon Homme, Brookings, Brown, Brule, Day, Butte, Davison, Charles Mix, Clark, Clay, Codington, Corson, Hyde, Buffalo, Sully, Perkins, Potter, Roberts, Sanborn, Shannon, Hughes, Stanley, Minnehaha, Todd, Tripp, Turner, Union, Walworth, Yankton, Spink, Marshall, Jackson, Jerauld, Jones, Kingsbury, Lake, Lawrence, Pennington, Lyman, Moody, McCook, McPherson, Meade, Mellette, Miner, Ziebach, Lincoln

1161 (2/26-27/97)
Turner, Perkins, Pennington, Moody, Minnehaha, Meade, Lake, Hutchinson, Harding, Butte
1173 (4/5-6/97)
Gregory, Deuel, Dewey, Douglas, Edmunds, Fall River, Hutchinson, Grant, Custer, Haakon, Hamlin, Hand, Hanson, Harding, Aurora, Faulk, Campbell, Beadle, Bennett, Bon Homme,

Brookings, Brown, Brule, Day, Butte, Davison, Charles Mix, Clark, Clay, Codington, Corson, Hyde, Buffalo, Sully, Perkins, Potter, Roberts, Sanborn, Shannon, Hughes, Stanley, Minnehaha, Todd, Tripp, Turner, Union, Walworth, Yankton, Spink, Marshall, Jackson, Jerauld, Jones, Kingsbury, Lake, Lawrence, Pennington, Lyman, Moody, McCook, McPherson, Meade, Mellette, Miner, Ziebach, Lincoln

1620 (11/27-29/05)
Grant, Beadle, Bon Homme, Brookings, Brown, Charles Mix, Clark, Codington, Davison, Day, Deuel, Aurora, Edmunds, Spink, Gregory, Hamlin, Hanson, Hutchinson, Jerauld, Kingsbury, Marshall, Miner, Roberts, Sanborn, Douglas

1759 (5/1-3/08)
Bennett, Butte, Harding, Jackson, and Perkins

Wisconsin
496 (3/19-20/76)
Manitowoc, Columbia, Crawford, Dane, Dodge, Fond du Lac, Grant, Green, Iowa, Calumet, Lafayette, Waukesha, Milwaukee, Ozaukee, Richland, Rock, Sauk, Sheboygan, Vernon, Walworth, Washington, Jefferson

3069 (1/13-14/79)
Racine, Milwaukee, Kenosha

3163 (12/15-17/00)
Waukesha, Walworth, Sheboygan, Rock, Racine, Ozaukee, Milwaukee, Manitowoc, Kewaunee, Kenosha, Green, Door, Dane, Columbia